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PROLIFERATED GROUND-BASED, LONG WAVE, TRANSMITTING SYSTEMS

Volume II — Antenna Subsystems

AD A100133

Analytical Systems Engineering Corporation
5 Old Concord Road
Burlington, Massachusetts 01803

31 March 1980

Final Report for Period 1 August 1979—28 March 1980

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This volume presents an evaluation of the design, performance, deployment methods, and costs for alternative VLF/LF transmitting antenna concepts. The results and findings contained in this volume (Volume 2) are used to support the feasibility assessment and cost performance trade off of proliferated ground-based, long wave, transmitting systems which is presented in Volume 1. Although the antenna concept evaluation focuses upon communication system application, the fundamental deviations are also included to enable re-evaluation of the parameters for different system design alterations.

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CONVERSION TABLE

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
cal (thermochemical)/cm^2§	mega joule/m^2 (MJ/m^2)	4.184 000 X E -2
calorie (thermochemical)§	joule (J)	4.184 000
calorie (thermochemical)/g§	joule per kilogram (J/kg)*	4.184 000 X E +3
curie§	giga becquerel (GBq)†	3.700 000 X E +1
degree Celsius‡	degree kelvin (K)	$t_K = t°_C + 273.15$
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	$t_K = (t°_F + 459.67)/1.8$
electron volt§	joule (J)	1.602 19 X E -19
erg§	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)§	gray (Gy)*	1.000 000
kilotons§	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4.214 011 X E -2
pound-mass/foot^3	kilogram-meter^3 (kg/m^3)	1.601 846 X E +1
rad (radiation dose absorbed)§	gray (Gy)*	1.000 000 X E -2
roentgen§	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The gray (Gy) is the accepted SI unit equivalent to the energy imparted by ionizing radiation to a mass of energy corresponding to one joule/kilogram.
†The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
‡Temperature may be reported in degree Celsius as well as degree kelvin.
§These units should not be converted in DNA technical reports; however, a parenthetical conversion is permitted at the author's discretion.

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SECTION 1
INTRODUCTION

Currently used ground-based Very Low Frequency/Low Frequency (VLF/LF) transmitting stations are large facilities occupying several hundred acres. The land area is needed primarily for the antenna subsystem which generally consists of one or more tower structures on the order of 300 to 400 meters in height. The towers are supported by a series of guy wires extending to a ground anchor location a distance usually equal to the height of the tower. The size and complexity of fixed location ground-based VLF/LF antenna subsystems impose severe restrictions upon system survival and endurance in a hostile environment.

Smaller and less complex transmitting antennas are examined in this report to identify antenna concepts which can reduce or eliminate problems of system survival and endurance. The transmitting antennas considered herein are categorized by the method in which the radiating components of the antenna are supported. There are three categories considered: 1) Transportable Tower, 2) Fixed Location Tower and 3) Tethered Balloon.

These categories generally represent three groupings of antenna heights resulting in performance differences among the groups. Extremely short antennas, represented by the transportable tower designs, offer a high degree of mobility, but exhibit very low performance capability. Fixed location towers are taller and exhibit better performance at the sacrifice of mobility. The loss of mobility can partly be compensated by using a large number of geographically dispersed antennas. Tethered balloon designs can offer a high degree of performance by achieving greater antenna heights and offer a high degree of mobility. However, tethered balloon antennas are more susceptible to adverse environmental conditions.

Within each antenna category several alternatives are examined. The alternatives differ in terms of radiating element configuration, physical dimensions and the components used within the system. The alternatives are evaluated to identify and assess technical, operational and cost characteristics. The technical characteristics include discussions of the antenna concept, its design and the electrical performance which theoretically could be achieved. Operationally, the antenna configuration is evaluated in terms of deployment methods and requirements. The costs for an antenna configuration are estimated to determine the acquisition and the Operation and Maintenance (O&M) costs. The acquisition costs include costs associated with Research, Development, Test and Evaluation (RDT&E) and production.

For deployment, the equipment and resources considered have been limited to that of and required for the antenna subsystem. The antenna subsystem is composed of those components from the point at which the power amplifier connects to the antenna coupler terminal through the signal radiating elements. Other components such as a source of primary power, the power amplifier and that for development of the signal to be transmitted are needed for a complete transmitting station but are not included within the discussions and assessments contained in this volume. A complete transmitter system is analyzed in Volume I.

SECTION 2
APPROACH METHODOLOGY

2-1 INTRODUCTION

Inasmuch as many of the design considerations are common to all three groups of antennas, we will first develop a general design approach in this section as basic design pattern relating efficiency vs. frequency and bandwidth vs. frequency for easy comparison of all antennas in the basic groups; short mobile towers, fixed towers and balloon supported antennas.

2-2 DESIGN ENGINEERING

Associated with design engineering are the critical electrical and mechanical design aspects of VLF/LF transmit antenna subsystems. A method for evaluation of two fundamental performance parameters, namely efficiency and bandwidth as a function of frequency, is presented.

2-2.1 Electrical Design

In general, our frequency range of interest (VLF/LF) imposes many restrictions upon the efficient radiation of energy from an antenna. The efficiency with which an antenna couples energy from a transmitter to the propagation medium is dependent upon the radiation resistance and all the system losses. These include ground losses, copper losses and loading coil losses.

2-2.1.1 Radiation Resistance. Radiation resistance is a measure of the ability of an antenna to convert transmitter power into electromagnetic radiating energy. The radiation resistance of an antenna is a function of the effective height of that antenna, which is:

$$h_e = \frac{\lambda \sin^2 (\pi h/\lambda)}{\pi \sin (2\pi h/\lambda)} \tag{1}$$

where: h_e = effective height

h = actual antenna height

λ = wavelength

At VLF/LF, most practical antennas are electrically short and for electrically short antennas the current distribution is basically triangular. Consequently the effective height reduces to:

$$h_e = h/2 \tag{2}$$

However, if an electrically short antenna is fully top loaded, the current distribution is essentially constant and therefore:

$$h_e = h \tag{3}$$

At the same time, if the capacitive top loading is formed by guy wires suspended from the top of the antenna towers there is a negative vertical component of current which reduces the effective height. Pierce et. al.[(1)] have determined, through both theoretical studies by Pierce and model studies by Woodward, that the effective height of a grounded tower with a guy wire top hat is approximately two thirds the average height of the tower and the height above ground of the end of the active guy. In other words:

$$h_e = 1/3\ (h+h'') \tag{4}$$

References (1) Pierce, J.A., W. Palmer, A.D. Watt and R.H. Woodward, "System Specification and Implementation", <u>OMEGA A World Wide Navigation System</u>, DDC No., AD 630900.

where h" is the height above ground of the end of the active guy. As a result it is possible for the effective height to be less than one half the actual height depending upon the amount of top loading. In practice optimum top loading often dictates this situation. This will be discussed in greater detail in paragraph 2-2.1.3.

Once the effective height has been determined, it becomes possible to estimate the radiation resistance. For electrically short antennas ($h < \lambda/4$) the radiation resistance (R_{rad}) is given by:

$$R_{rad}(\Omega) = 160\ \pi^2\ (h_e/\lambda)^2 \tag{5}$$

For closely spaced antennas there exists a mutual coupling of impedances such that the driving point impedance is equal to the sum of the self-impedance plus the mutually induced impedances. For the Multiple Tuned Umbrella Array:

$$\text{total } R_{rad} \quad R_{rad} \quad\ + .9 + .9) = 2.8\ R_{rad} \tag{6}$$

Radiation resistance for the quarter wavelength monopoles is well established in theory at 36.6 ohms. This value is employed for the quarter wave antennas under investigation.

2-2.1.2 Ground Losses. Antenna loss resistance seen at the input terminals consists of: copper losses, dielectric losses in the insulators, and ground losses. In a well designed antenna, both the copper and dieletric losses should be negligible when compared to the ground losses. As such, these factors are ignored in this evaluation. Ground loss results when antenna currents return through a ground which is not a perfect conductor.

One form of this loss occurs when radial current flows in the lossy ground as a result of the magnetic field which is in turn generated by the vertical down lead current. This loss is often referred to as

H-field loss. The second form of this loss occurs when displacement currents from the antenna flow through the lossy ground. This loss is often referred to as E-field loss.

Extensive calculations of the ground impedance of a vertical monopole antenna have been made by Maley et. al.[2] In their report, these investigators have generated numerous curves of ground impedance variations as a function of electrical height and parametric in ground screen size. These curves have been generated for various conditions of wave tilt (δ), loss tangent (ψ), top loading (α), number of ground screen radials (N) and normalized wire radius (c). A brief discussion of these different factors is useful to understanding these results.

Wave tilt is given by the relation:

$$\delta = \delta' \left[\frac{1}{1 + i\,(\delta')^2 \varepsilon} \right]^{1/2} \tag{7}$$

where:

$$\delta' = \left[\frac{\omega\, \varepsilon_o}{\sigma} \right]^{1/2} \tag{8}$$

For the frequency range of interest (VLF/LF) where the angular frequency $\omega = 2\pi f$, and for geographic locations where the ground conductivity and permittivity are characterized by:

$\varepsilon_o = 8.85 \times 10^{-12}$ F/m
$\sigma = 10^{-3}$ mhos/m
$\varepsilon = 10$

---

(2) Maley, S.W., R.J. King and L.R. Branch "Theoretical Calculations of the Impedance of a Monopole Antenna with a Radial Wire Ground System on an Imperfectly Conducting Half-Space," AFCRL-63-583, December, 1963.

equation (7) reduces to:

$$\delta = \delta' \tag{9}$$

Given the general dimensions of the antenna system (extremely short electrically), the incremental ground losses (ΔR) are directly proportional to the wave tilt. In other words ΔR varies linearly with δ.

Furthermore, the loss tangent angle (Ψ) which is defined by:

$$\Psi = 1/2 \tan^{-1}\left[(\delta')^2 \varepsilon\right] \tag{10}$$

becomes zero ($\psi = 0$) since $(\delta')^2 \varepsilon \ll 1$, which corresponds to negligible displacement currents and a relatively good conducting earth.

Top loading may be expressed as:

$$\alpha = \beta\ (h + a) \tag{11}$$

where: α is the top loading factor, a is the equivalent length of the top hat and $\beta = 2\pi/\lambda$ is the wave number.

Full top loading implies a constant current distribution for electrically short antennas. Mathematically this is stated:

$h + a = \lambda/4$ and therefore:

$$\alpha = \pi/2 \tag{12}$$

Examination of Maley's calculated results reveals that, for electrically short antennas with electrically small ground planes, the total ground loss is minimally affected by the number (N) of ground wires. Maley has also shown that for very small values of b/λ, the wire size has practically no effect. The normalized wire radius of $c = 10^{-6}$ corresponds to approximately 1 cm diameter wire or smaller for the antenna system.

Maley's data is reproduced herein as Figure 1 and is used for the determination of the ground loss. Examination of Figure 1 reveals that for small values of both h/λ and b/λ the magnitude of the ground impedance remains essentially constant. This is true for a fixed value of wave tilt. However, as was previously noted, ΔR varies linearly with δ. Therefore, in order to determine the correct value of ground loss resistance (R_g), one must adjust the ΔR obtained from the curve used in Figure 1 by the ratio of his particular value of δ to a value of $\delta = 0.03$. The total ground loss for a vertical monopole antenna is then given by the relation:

$$R_g(\Omega) = (\delta/.03)\ \Delta R \tag{13}$$

H-field and E-field losses for the case of no ground plane are based on the treatment by A.D. Watt[3] with appropriate modifications. The H-field losses are computed using the following expression:

$$R_H = 7.32 \times 10^{-4} \sqrt{\frac{f}{\sigma}} \log_{10} h + 1.59 \times 10^{-4}\ h^2 \left\{ \frac{1}{h^2} - \frac{4\pi^2}{2\lambda} \right\} \tag{14}$$

where: R_H = H-field loss resistance (ohms)

f = frequency (Hertz)

σ = conductivity (mhos/m)

h = antenna height (meters)

λ = wavelength (meters)

E-field losses are calculated by the expression

$$R_E = \frac{.577 \ln (2h) + .88}{f^{1/2}\ \sigma^{3/2}\ h^2} \tag{15}$$

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(3) Watt, A.D., <u>VLF Radio Engineering</u>, Pergamon Press, New York, 1967

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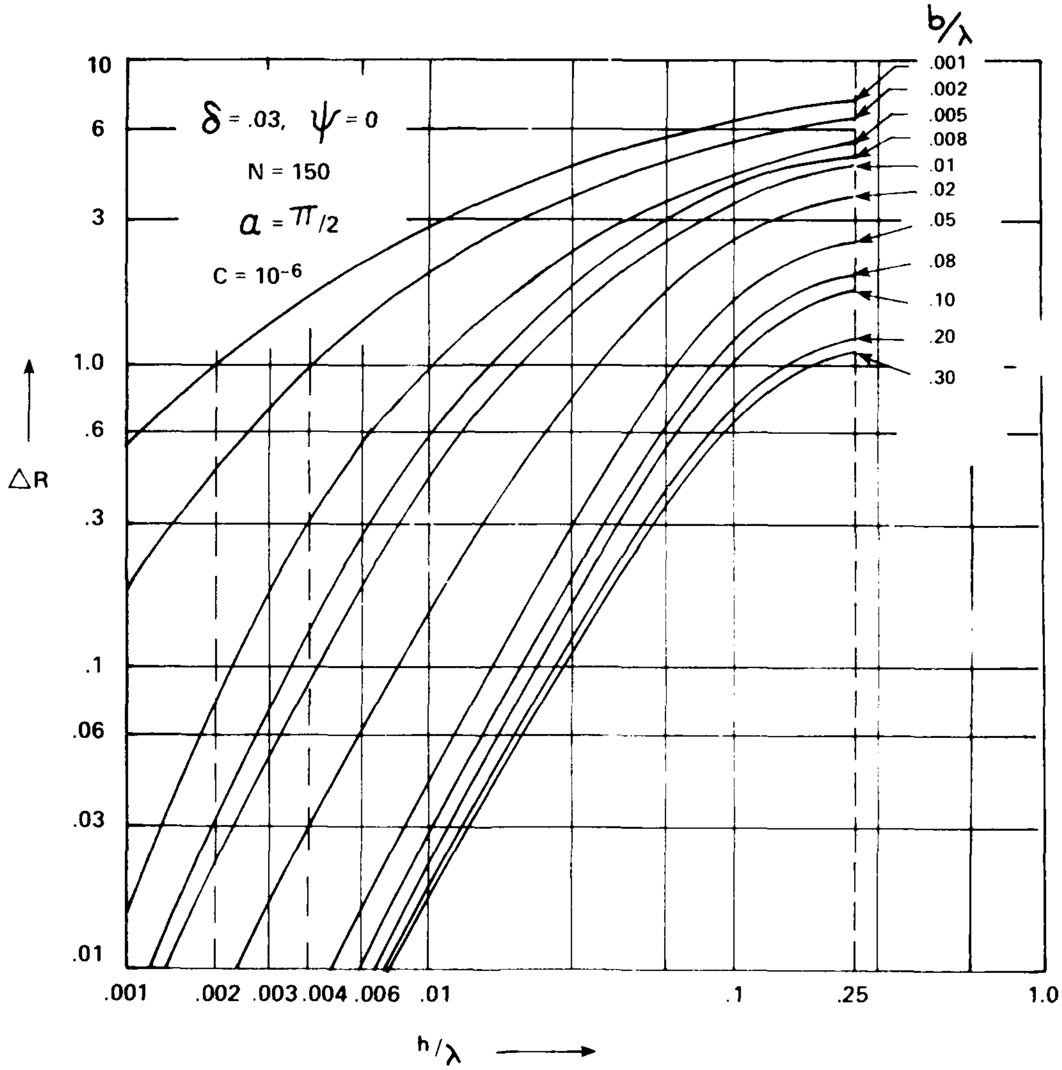


Figure 1. Ground Losses.

2-2.1.3 Top Loading. Antenna capacitance is generally determined by both the vertical monopole tower and the top loading structure. For a single vertical wire or conductor above the earth's surface, the intrinsic capacitance (C) can be determined from the following expression:

$$C(pF) = \frac{24.16\ h}{\log(2h/d) - k} \tag{16}$$

Here d is the diameter of the wire and k is a correction factor which is proportional to the ratio of the height above ground of the lower end of the wire to the total length of the wire.

Top loading increases the capacitance of an antenna by essentially forming a parallel plate capacitor where the capacitance is given by the classical expression:

$$C = A_{eff}\ \varepsilon_o/h \tag{17}$$

Here the effective area of the top loading structure A_{eff} is given by the sum of the physical area and the fringe area. In the case of the Multiple Tuned Umbrella Array, the top loading structure is hexagonal in shape. Consequently the physical area (A_{phy}) is represented by:

$$A_{phy} = (3/2)\sqrt{3}\ \ell^2 \tag{18}$$

and the fringe area = A_{fr} is defined by:

$$A_{fr} = \text{perimeter x h} = 6\ell h \tag{19}$$

where ℓ is the length of a side of the hexagon.

Combining the above expressions for capacitance gives:

$$C(pF) = 13.26\ \ell\left[(\sqrt{3}\ \ell/h) + 4\right] \tag{20}$$

The vertical monopole and top loading capacities are considered to be in parallel.

When the top loading is formed by the guy wires, the capacitance can be determined in the following manner, taken from A.D. Watt[3]. As shown in Figure 2 the chord length of the active guy is defined as h'. The ratio of the active guy chord length to the actual tower height (h'/h) determines the increase in capacity relative to a vertical monopole antenna. Figure 3 shows the relative increase in capacity as a function of the number of active guys and is parametric in h'/h. As can be seen, the greater the number of active guys and the larger the parameter h'/h one uses, the greater is the capacitance.

When guy wires are used to form the capacitive top hat there exists a negative component of current. This results in a decrease of effective height relative to a flat top hat. In fact, the greater the value of the parameter h'/h and the greater the number of active guys one uses, the larger is the decrease in effective height. This effect can be seen in Figure 4.

There is a tradeoff in choosing optimum values of h'/h and number of active guys. It has been shown by Watt that the radiated power is directly proportional to C^2 and h_e^2. For example, examination of Figures 3 and 4 reveals that by using 16 active guys and a value of 0.8 for h'/h the maximum radiated power possible for a constant limiting voltage increases by a factor of 21. The bandwidth on the other hand is mainly proportional to C and as such would increase by a factor of approximately 5 in our example.

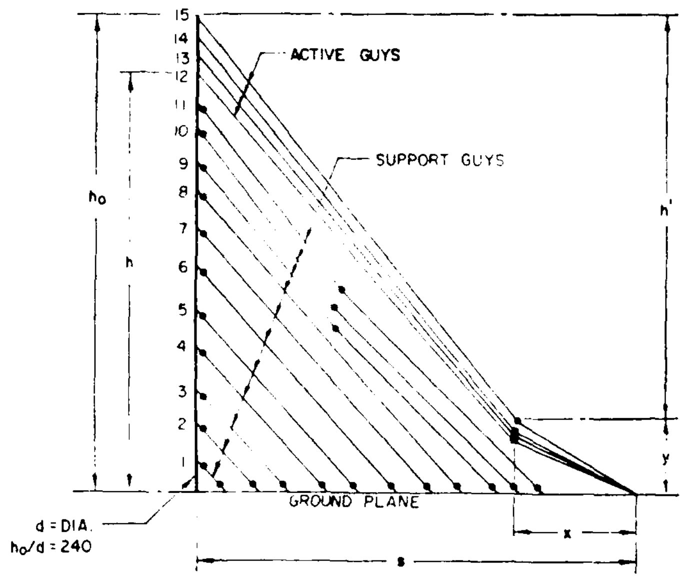
2-2.1.4 Loading Coil Having determined the capacitance and corresponding reactance as a function of frequency for a given antenna, there remains the design of the loading or tuning coil. F. Terman[4] has given the following relation for coil inductance (L):

---

(3) ibid

(4) F.Terman, Electronic & Radio Engineering, McGraw-Hill Co., N.Y. 1955

GUY LEVEL	h/h_o	h/s	$h'/h_o=0.8$		$h'/h_o=0.7$		$h'/h_o=0.6$		$h'/h_o=0.5$	
			x/s	y/h_o	x/s	y/h_o	x/s	y/h_o	x/s	y/h_o
15	1.00	1.11	0.26	0.154	0.37	0.24	0.48	0.34	0.58	0.44
14	0.966	1.07	0.26	0.13	0.37	0.21	0.48	0.305	0.58	0.40
13	0.930	1.33	0.26	0.13	0.37	0.21	0.48	0.30	0.58	0.39
12	0.886	0.98	0.26	0.126	0.37	0.196	0.48	0.28	0.58	0.37
11	0.833	1.13	0.60	0.42	0.53	0.42	0.53	0.42	0.42	0.53
10	0.773	1.13	0.59	0.39	[illegible]	0.39	0.52	0.39	0.39	0.52
9	0.707	1.13	0.59	0.36	0.52	0.36	0.52	0.36	0.36	0.52
8	0.633	1.13								
7	0.556	1.13								
6	0.476	1.13								
5	0.393	1.13								
4	0.310	1.13								
3	0.266	1.13								
2	0.150	1.25								
1	0.076	1.15								



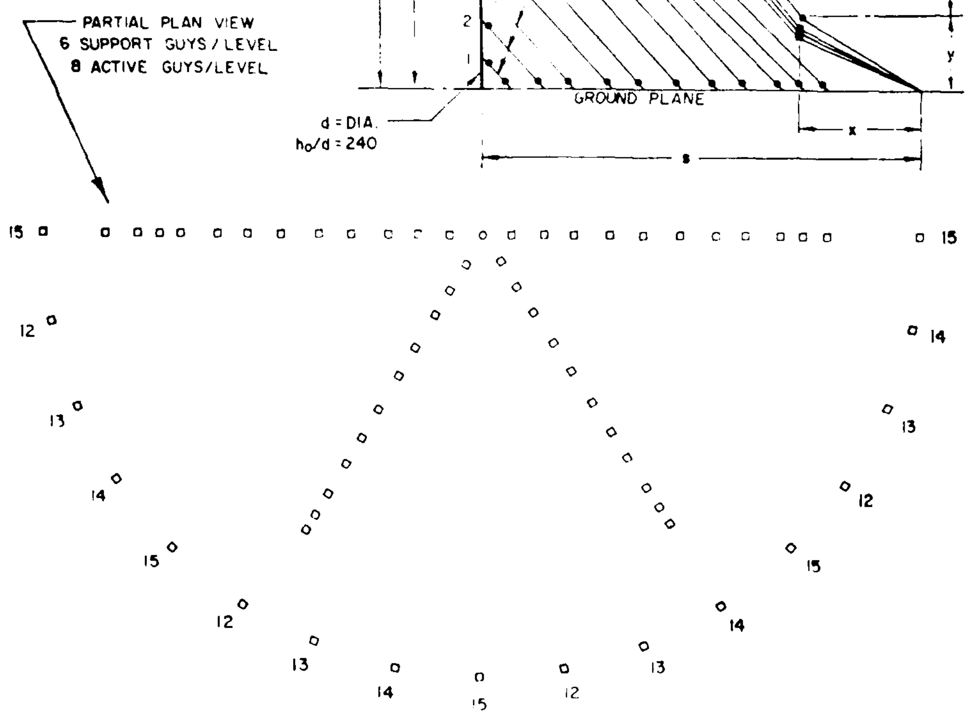


Figure 2. Top Loaded Vertical Radiator.

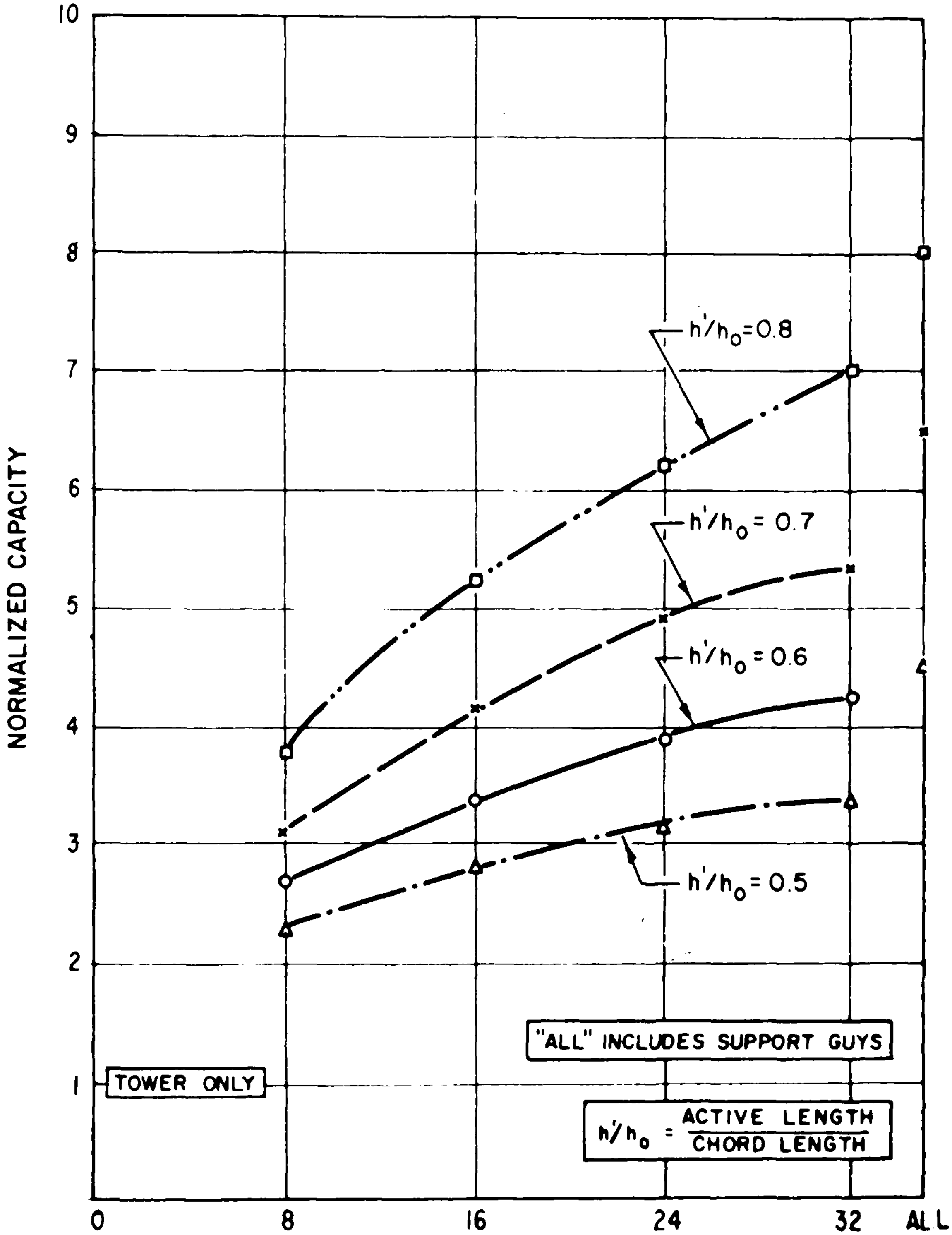


Figure 3. Normalized Static Capacitance of a Top Loaded Vertical Radiator

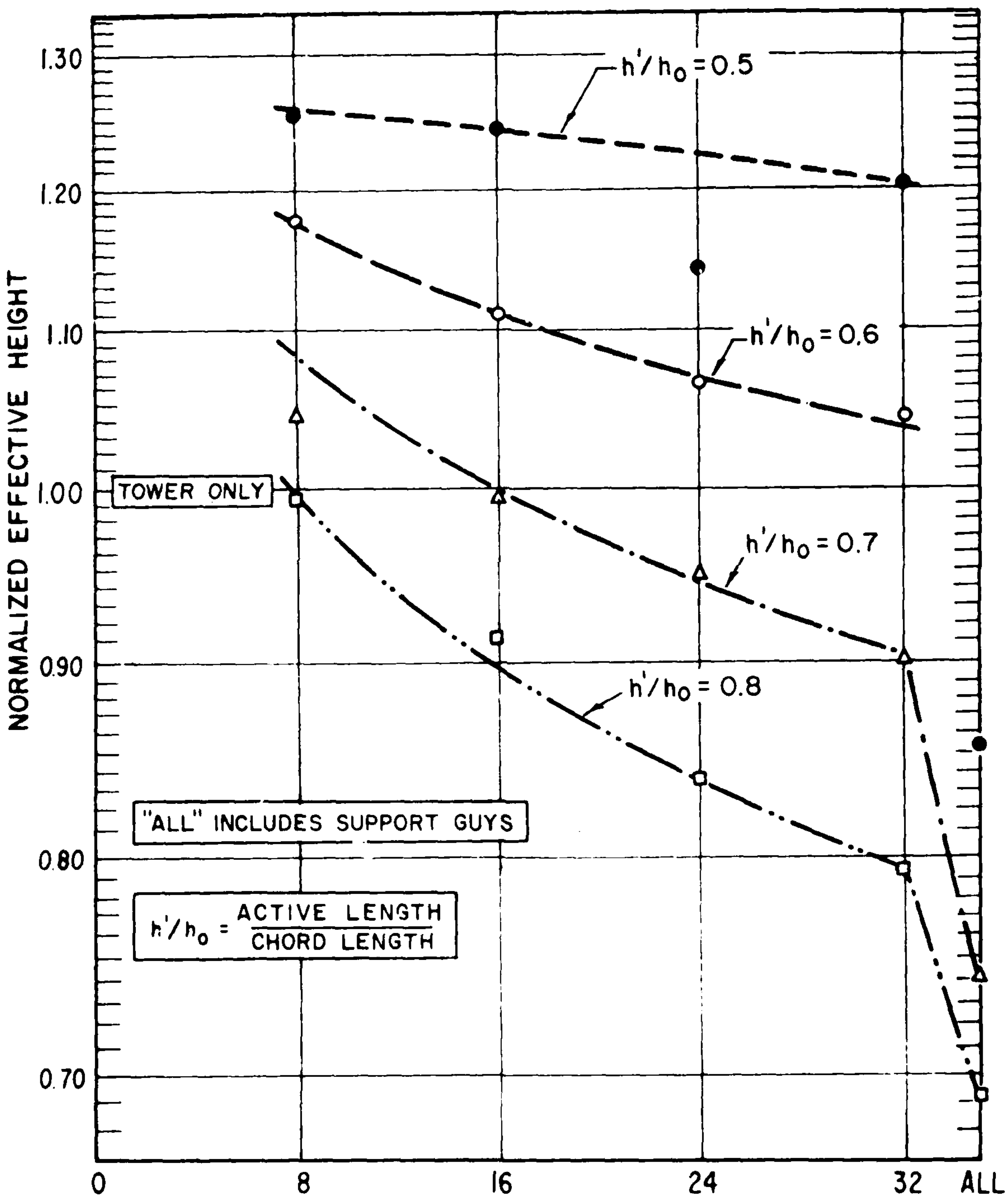


Figure 4. Normalized Effective Height of a Top Loaded Vertical Radiator.

$$L(H) = 3.937 \times 10^{-5}\ F\ n^2\ D \tag{21}$$

The value of F is a function of the form factor D/ℓ of the tuning coil, where D is the coil diameter and ℓ is the length or height of the coil. Figure 5 shows the variation of F with D/ℓ.

The inductance required for tuning an antenna is derived from

$$X = \frac{1}{2\pi f C} = 2\pi f\ L \tag{22}$$

where X is the antenna reactance.

Combining expressions (20) and (21) enables determination of the number of turns required for the tuning coil.

$$n = \left[\frac{4.04\ X}{f\ (kHz)\ FD}\right]^{1/2} \tag{23}$$

Tuning coil losses (R_c) can now be determined from the following expression given by Watt.

$$R_c(\Omega) = \frac{\ell}{d} \left[\frac{\mu f}{\pi\sigma}\right]^{1/2} \tag{24}$$

where ℓ is the total length of wire in the solenoid and specifically $\ell = n\pi D$, d is the wire diameter, the conductivity of copper is $\sigma = 5.8 \times 10^7$ mhos/m and the permeability of copper is $\mu = \mu_o = 1.26 \times 10^{-6}$ H/m

The actual tuning coil losses are more correctly given by

$$R_c(\Omega) = \frac{n\pi D}{d} \left[\frac{\mu f}{\pi\sigma}\right]^{1/2} K \tag{25}$$

where K is a correction factor, due to proximity effects between adjacent windings of the solenoid or tuning coil. For a spacing to wire diameter ratio of 2, the correction factor, K, has a value of approximately 1.15.

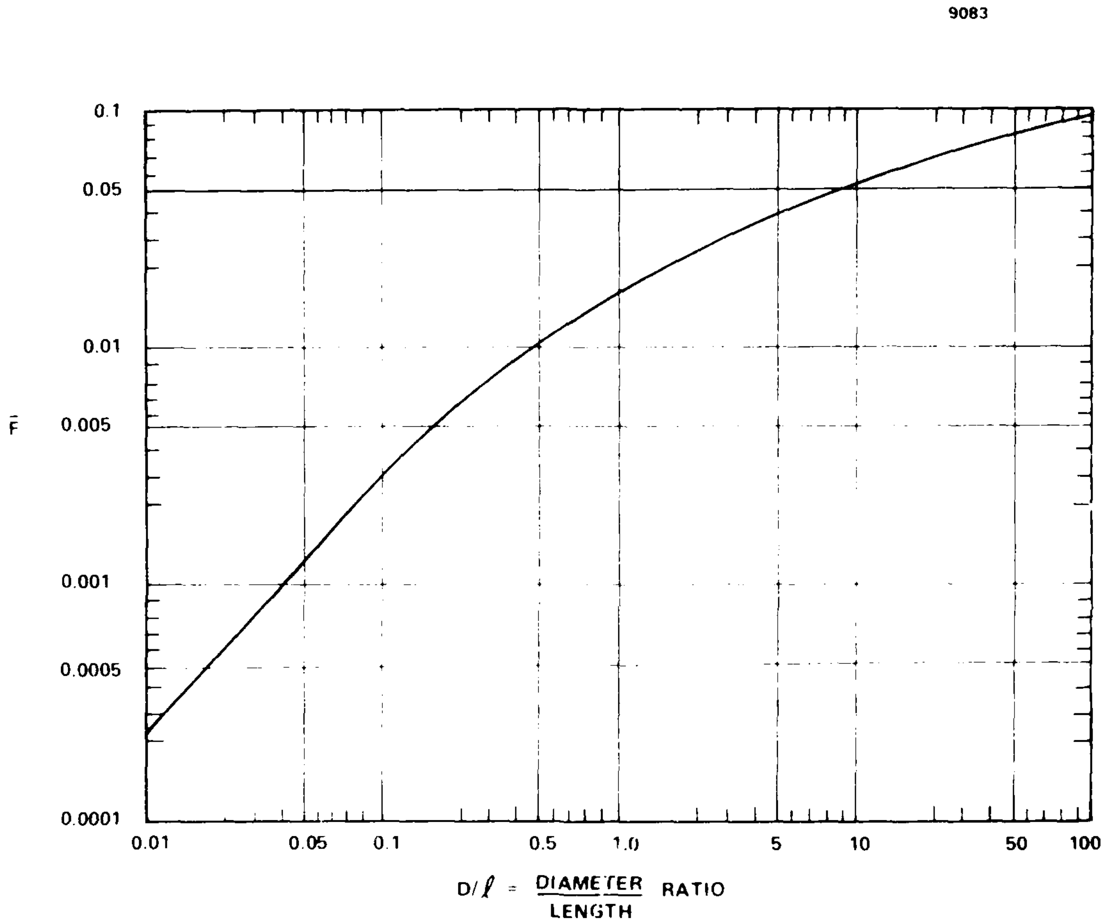


Figure 5 Factor F for Single-Layer Solenoid
(Source: A.D. Watt, VLF Radio Engineering pg 99)

2-2.1.5 Efficiency. One of the most important properties of a transmitting antenna is the efficiency with which it converts transmitter power to radiated power. Efficiency may be defined as the ratio of power radiated to total input power. Since the power radiated is proportional to the radiation resistance, the efficiency (η) of an antenna is readily calculated from the following expression:

$$\eta = R_{rad}/R_{total} \tag{26}$$

where R_{total} is the sum of all loss resistances plus the radiation resistance. If one includes the tuning coil losses, then the entire antenna system efficiency in percentage is given by:

$$\eta = \frac{R_{rad}}{R_{rad} + R_g + R_c} \times 100\% \tag{27}$$

It must be remembered that the above expression neglects the copper losses in the antenna as well as the equivalent dielectric losses. Generally this is permissible in a well designed antenna.

However, for the case of the quarter wavelength balloon borne monopole, copper losses are important since the lift capability of the balloon or aerostat must be traded against the weight of antenna cable. From this point of view, a small diameter cable is desirable although copper losses are increased. The overall effect of smaller diameter cable is an increase in copper loss and bandwidth with a resulting decrease in weight and efficiency. Consequently, copper loss is included in the efficiency computation for the quarter wave monopole.

2-2.1.6 Bandwidth. Another transmit antenna property of equal importance is the 3 db bandwidth. A. D. Watt has derived the following expression for bandwidth (BW) as:

$$BW(Hz) = \frac{1.11 \times 10^{-7} h_e^2 f^4(kHz)\ C(\mu f)}{\eta} \tag{28}$$

It should be noted that η in the above expression is not expressed in percentage and that the bandwidth is defined by the 3 dB points.

Of great significance is the fact that efficiency can be traded off for increased bandwidth by the addition of a series damping resistor. By increasing the value of R_{total}, the efficiency is decreased and the bandwidth is increased by the same proportion. This can be seen by combining equations (25) and (27). Sometimes it becomes necesary to sacrifice efficiency for increased bandwidth, particularly in wide band communication systems.

The 3dB bandwidth for the quarterwave monopole antenna is computed using the following expression.

$$BW = 2\,\frac{(R_{rad} + \rho\ell + R_H)}{dX/df} \qquad (29)$$

where BW = 3dB bandwidth (kHz)

R_{rad} = Radiation resistance (ohms)

R_H = H-field loss resistance (ohms)

ρ = resistivity (ohms/meter)

ℓ = length (meters)

dX/df = rate of change of reactance (ohms/meter/kHz)

2-2.1.7 Power Radiated. By definition an antenna radiates power in proportion to its radiation resistance. Specifically the power radiated (P_{rad}) is given by:

$$P_{rad}\ (W) = I^2 R_{rad} \qquad (30)$$

where I is the rms antenna current. Based on this relationship and knowing both the radiated power requirements and the estimated radiation resistance, one can determine the antenna current. From this information and knowing the capacitive reactance of the antenna, the maximum voltage (V_{max}) appearing on the antenna can be calculated from the following expression.

$$V_{max}\ (V) = 1.4\ I\ X_C \tag{31}$$

Given the present day technology of insulation development according to Martin and Carter[5], 250,000 volts is the maximum antenna voltage that can be tolerated. A more practical value of antenna voltage limitation used by many in the VLF antenna field is 150,000 volts. This voltage limitation in turn specifies the absolute minimum antenna capacitance and consequently top hat size. Conversely, a given top hat structure which defines the antenna capacitance limits the maximum radiated power possible.

2-2.2 Mechanical Design

Several of the antenna concepts presented in Sections 3 and 4 present potential problem areas and structural limitations in mechanical design. In one configuration, the Multiple Tuned Umbrella Array, the antenna elements are suspended between several towers. Due to the long span between towers an evaluation of the antenna wire is necessary to ensure that the breaking strength of the wire is not exceeded.

Another antenna configuration uses a tower to support a top hat assembly. The design of the top hat, in order to be suitable for adequate electrical performance, is such that the weight may exceed the structural support limits of the tower, unless design attention is given to the top hat material used.

In both cases, the mechanical design of the antennas must consider the effect of icing and the combined effect of icing and wind to ensure that a sufficient safety factor remains.

Tethered Balloon antenna systems are considered in Section 5. Such systems must be designed whereby, the lift capacity of the balloon is sufficient to support the weight of the antenna system at the altitudes considered.

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(5) Martin, C.A. and P.S. Carter "Low Frequency Antennas", chapter 19, Antenna Engineering Handbook, Ed. H. Jasik, McGraw Hill Book Co., 1961.

The common mechanical design problems are analyzed here.

2-2.2.1 Mechanical Evaluation of Catenaries. The mechanical design fundamentals presented in the following paragraphs are used to evaluate the mechanical performance of a suspended catenary. In one case, the catenary is suspended from two equal elevation supports. In the other case, the catenary is suspended from unequal elevation supports. This has application to the monopole with guy top hat and multiple antenna arrays.

Catenary Suspended From Equal Elevation Supports.

When a catenary is suspended from two equal elevation supports, the maximum tension occurs at the supports. To determine the minimum mechanical load that the catenary must support, an approximation can be used (assuming a tightly stretched wire) by:

$$\frac{T_{max}}{W_w} = s + \frac{a^2}{8s} \qquad (32)$$

where:

W_w = weight per unit length of wire

s = sag of wire (distance center of wire drops below supported ends)

a = wire span (horizontal distance between supports)

T_{max} = maximum wire tension

The maximum tension a wire can withstand is given in terms of its tensile strength (ν) by the relationship:

$$T_{max} = \nu A \qquad (33)$$

where A is the cross sectional area of the wire.

The weight per unit length of the wire is:

$$W_w = \rho g A \qquad (34)$$

where ρ is the mass density of the wire material.

Using equations (31) and (32), the actual mechanical loading capability of the catenary consisting of any wire material is determined by the relationship:

$$\frac{T_{max}}{W_w} = \frac{\nu A}{\rho g A} = \frac{\nu}{SG\rho_{H_2O} g} \tag{35}$$

where SG is the specific gravity of the wire material.

The maximum safety factor of given wire material is determined by using the ratio of calculated values from equations (33) and (30). Aluminum wires have a safety factor of about 15.4, whereas the safety factor for steel wires is approximately 46.7 for a 150 m catenary with a 6 m sag.

These safety factors are reduced to account for the effects of icing and wind.

Icing increases the weight per unit length of the wire. The weight per unit length increase due to the ice (W_{ice}) is

$$W_{ice} = SG_{ice}\ \rho_{H_2O} g \quad \frac{\pi}{4}\left(d_{ice}^{\ 2} - d_{wire}^{\ 2}\right) \tag{36}$$

where $SG_{ice} = 0.92$.

Assuming a wire to be 1.25 cm and an ice build-up on the wire of 1.25 cm thickness, the safety factor for aluminum wire decreases to 4.24.

The drag force per unit length of wire, (WF/ℓ) due to wind is

$$(WF/\ell) = C_D \frac{1}{2} \rho_{air} V_\infty^{\ 2}\ d \tag{37}$$

Where C_D is the drag coefficient of the wire for wind blowing normal to the wire with velocity, V_∞ C_D = 1.2 for normal flow over a cylinder. The density of air (ρ_{air}) is 1.2 kg/m^3.

The wind drag force usually acts horizontally on the wire. The worst possible case is when the wind acts vertically downward, thereby increasing the effective weight of the wire. Considering this worst possible case,

$$W = W_w + W_{ice} + (WF/\ell) \tag{38}$$

Considering an example with 100 km/hr wind on a 1.25 cm diameter aluminum wire with a 0.75 cm ice build-up, the combined loading decreases the safety factor to 2.25.

Catenary Suspended From Unequal Elevation Supports.

An example of a catenary suspended from unequal elevation supports is the guy wire of a tower. For these configurations, the span of the guy wire is the horizontal distance from the base of the tower to the ground attachment anchor.

The basic mechanical load that this type of catenary must support is determined using the relation,

$$\frac{T_{max}}{W_w} = h + C_p \tag{39}$$

where:

h = the tower height

C_p is the catenary parameter and can be determined fom the relation,

$$\frac{h}{C_p} = \cosh\left(\frac{B}{C_p} - 1\right) \tag{40}$$

which is a transcendental equation solved by iteration for C_p. For this equation, B is the guy wire span.

Assuming a tower/guy configuration where h=300 m and B=600m, C_p in equation (38) is 644.4m. Assuming aluminum guy wires are used, the safety factor using equations (33) and (37) is determined to be 7.86.

An ice build-up on the wire of 1.25 cm thickness lowers the safety factor to about 3.9.

Considering a combined ice and wind condition where the ice build-up is 0.75 cm in thickness and 100 km/hr winds, the safety factor is lowered to about 2.5.

2-2.2.2 Balloon Supported Radiator. In order to determine the appropriate size of balloon needed to support a radiating wire, the weight of said wire or wires, if a top hat is also to be included, must be known. From this the required lift or bouyancy of a balloon can be calculated.

The actual lift provided by a balloon can be estimated by the density of air displaced at a given altitude less the physical weight of the balloon. Furthermore, to provide stability and prevent blow down in a windy environment, aerodynamically shaped balloons called aerostats are employed. In fact properly designed aerostats exhibit a positive lift during windy conditions.

Let us assume that the gas to be used to inflate the balloon is helium. Then in order to calculate the payload or lift (L_b) we observe that

$$L_b = B_o - FL - W_{bag} \tag{41}$$

where:

B_o = bouyancy of helium in air
FL = free lift (10% recommended)
W_{bag} = weight of balloon bag

Given the volume (Vol) of air displaced by helium the bouyancy is expressed by

$$B_o = \text{Vol} \times \Delta \rho \tag{42}$$

where $\Delta\rho$ is the difference in density between air and helium at a given altitude. In particular

$$\Delta\rho = \rho_{air} - \rho_{He} \tag{43}$$

where

ρ_{air} = density of air
ρ_{He} = density of helium

More specifically the differential density (ΔP) can be determined as follows

$$\Delta\rho = \rho_{air}\left(1 - \frac{\rho_{He}}{\rho_{air}}\right) \tag{44}$$

furthermore, the density of a gas is proportional to its molecular weight such that

$$\frac{\rho_{He}}{\rho_{air}} = \frac{MW_{He}}{MW_{air}} \tag{45}$$

therefore combining equations (41), (42), (43), (44), and (45) results in the following expression for the payload which can be carried by an aerostat in no wind to a particular altitude.

$$L_b = .9 \text{ Vol } \rho_{air} \left(1 - \frac{MW_{He}}{MW_{air}}\right) - W_{bag} \tag{46}$$

Since the molecular weights of both helium and air are known constants ($MW_{He} = 4$ and $MW_{air} = 28.97$) equation (44) can be rewritten as follows:

$$L_b = .7757 \text{ Vol } \rho_{air} - W_{bag} \tag{47}$$

The density of air varies as a function of many variables, in particular altitude, temperature and geographic latitude. Tables of this information are available in the U.S. Standard Atmosphere Supplements 1966.

2-3 DEPLOYMENT CONSIDERATIONS

Fundamental in the evaluation of a deployment capability is the question "How can mobility be achieved?" For an emergency communication application the system should be available when needed; require minimal time to set-up from a stored configuration, and; require a small, unspecialized crew of personnel for set-up.

Two alternatives are available for antenna storage. When practical, storage on transport vehicles is considered in order to provide as much survivability through mobility as possible. When impractical to store the antenna on transport vehicles or when response time is of the essence, the antenna is "stored" in an installed, set-up state on a site awaiting the deployment of other transmitting station components. In the latter case, the antenna is exposed to the elements, reducing its probability of survival.

Intrinsic to establishing firm deployment parameters is the definition of the maximum time and crew size allowable to install and set-up the antenna. These factors influence the decision for storing the antenna in a transport configuration or in the set-up configuration. Our evaluation did not place specific limits upon maximum deployment times.

However, in the case of a fixed location tower consideration was given to the impact of installation and set-up. For this particular configuration, it is recommended that the tower be modified for VLF/LF operation and "stored" in the set-up state. This minimizes the skill specialties of an emergency deployment crew and avoids prolonged time impacts such as that associated with guy anchor installation.

The physical size of VLF/LF antennas and the emergency application of the system, place certain requirements on the site selected for the antenna. The site should be a location removed from urban and industrial areas; be accessible using land vehicles, and; be a location removed from probable target areas. The terrain should be reasonably flat and firm to support the weight of antenna components and the vehicles transporting the components.

To reduce the installation and set-up time of certain antenna configurations, determination must be made as to whether specific sites will be prepared in advance and the degree of advance site preparation. If advance site preparation is decided, then consideration must be given to equipment layout on the site.

In summary, the deployment factors considered include

a. A suggested deployment concept, with emphasis given to mobility,

b. Special or unique site requirements,

c. Highlights of the installation and set-up process,

d. The quantity and specialties of the crew personnel for installation and set-up, and

e. The types and quantities of transport vehicles.

2-4 COST METHODOLOGY

Each antenna configuration described in Sections 3, 4, and 5 is evaluated to assess the associated life cycle cost. This includes the cost for Research, Development Test and Evaluation (RDT&E) and production.

RDT&E costs are based on delivery of one unit; it also includes the non-recurring cost of design engineering, developmental and operational test and evaluation, technical publications and engineering data. Production costs are determined for optional buys of 10, 20, 40, and 80 systems. The learning curve theory has been applied to the multiple units produced, e.g., as the number of units produced is doubled, the cost of the second lot is reduced by 20% of the cost of the first lot. O&M costs are based upon deploying and maintaining the system four times per year over a period of 10 years. The cost includes maintenance personnel requirements to maintain and repair the system, operational spares, and vehicle maintenance and repair.

For each antenna configuration, RDT&E and production costs are determined by using the format of a work breakdown structure (WBS). The prime mission equipment (PME), e.g., hardware design, raw materials and integration and assembly, enables the determination of the configuration item cost and the scope and complexity of other items in the WBS.

The methodology is based on a bottom-up cost estimate, e.g., each WBS item is estimated according to the time required to perform certain tasks based upon experience with programs of similar complexity. Material cost quotations have been obtained as required. A systems integration contractor is assumed to design, fabricate, test and deliver the system; therefore, appropriate contractor raw materials and labor overhead factors are applied.

The RDT&E and production costs are presented as composite curves in each antenna configuration section. These costs vary as a function of the quantity of antenna systems acquired. The cost for one system reflects the associated RDT&E cost. The costs for more than one system includes the RDT&E cost of the first system plus the subtotal cost for the production units to give a total program cost.

SECTION 3
TRANSPORTABLE TOWER ANTENNAS

3-1 INTRODUCTION

The objective of low profile, transportable VLF/LF transmitting antenna systems is to provide improved system survivability during a trans-attack period. Antennas of this type may be stored until the post-attack period and then be transported to a suitable site and erected. As an alternative, the antennas could be pre-deployed since their relatively small size permits a degree of concealment in an unlikely target area. These antennas utilize erectable tower structures, either as the radiating element or as supporting structures for the radiating element. To enable transportability, the towers should be short. A practical limit is 60 meters.

By their intrinsic nature, low profile antennas achieve increased survivability at the expense of decreased radiation efficiency and transmission bandwidth. Monopole antennas in the height range of 30 to 60 meters are extremely small electrically in comparison to the wavelengths of VLF/LF. Nominal radiation efficiencies on the order of 0.01% or less generally result in the 30 kHz range. The use of multiple tower umbrellas can increase this to 1-3%

In addition to efficiency and bandwidth limitations, the low profile transmitting antennas are limited in the maximum power that can be applied to the antenna terminals. Antenna input power should be limited to less than 50 kW to minimize the conditions for corona onset. Corona is a physical hazard to the system.

Two distinctive transportable tower antenna configurations are evaluated in this section. One configuration is a single tower. Two versions with heights of 30 and 60 meters are evaluated. This configuration produces a nominal radiation efficiency of .07% at 30 kHz for a 30 meter tower (.58% for 60 meters). The second antenna

configuration is a Multiple Tuned Umbrella Array. This configuration is based upon a design developed by the Rome Air Development Center (RADC). The Multiple Tuned Umbrella Array utilizes seven towers to support an umbrella shaped radiating top hat. Two versions of this antenna configuration are evaluated. A 30 meter high version of this antenna (as developed by RADC) achieves a nominal efficiency of 0.78% at 30 kHz. An enhanced version which doubles certain physical parameters (e.g., 60 meters high, etc.) can achieve a nominal efficiency of 3.2% at 30 kHz.

These antenna configurations differ, not only in radiation efficiency, but also in size and complexity. An increase of radiation efficiency can be achieved by larger and more complex systems, but at an increase of cost and erection time. The design and deployment trade-off issues are presented in Section 3-4. Associated costs are presented in Section 3-5.

3-2 ANTENNA DESCRIPTIONS

First we will examine the physical and component characteristics of the two antenna configurations. This will serve as a baseline description for subsequent performance, deployment and cost assessments.

3-2.1 Single Tower Antennas

The single tower antenna makes use of a mobile telescopic tower which is transported in nested configuration on a trailer which is an integral part of the system. The erected tower can have a height in the range of 30 to 60 meters. In all cases top loading guy wires are used both to improve radiation performance and to support the tower structure. The antenna also utilizes a radial ground plane and a transportable antenna coupler. Figure 6 illustrates the configuration concept of the single tower antenna.

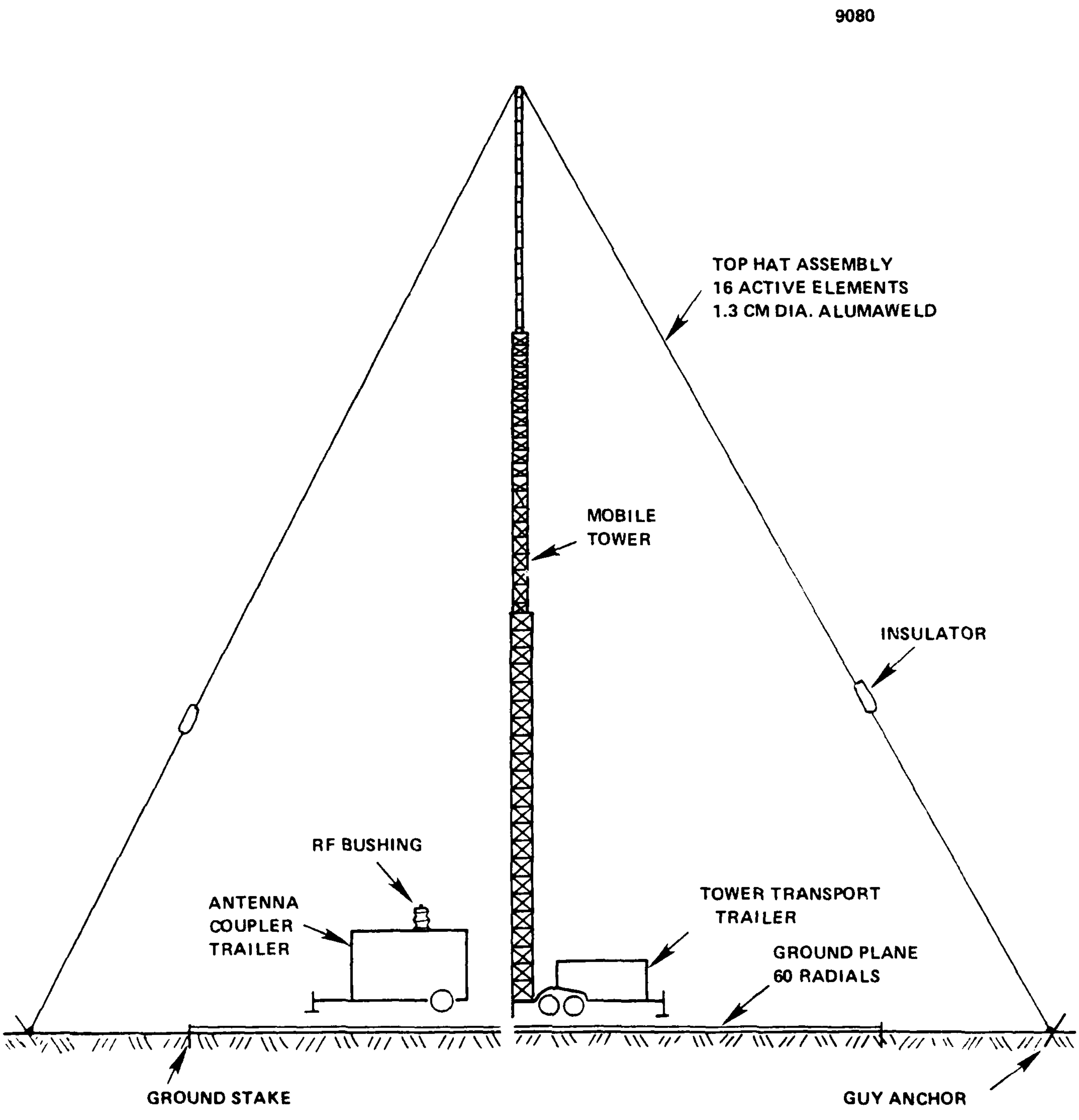

Figure 6. Single Tower Configuration.

3-2.1.1 Tower. The tower selected is a telescopic design for compactness in transport and to minimize difficulty for set up. Telescopic towers of this type have been developed by the Tri-Ex Tower Corporation and are currently available at heights up to 45 meters. A 60 meter version is under development. For evaluation, tower heights of 30 and 60 meters are considered.

A trailer is available for transport of the tower and contains an optional manual or motorized tower crank-up capability. The tower can be set up in approximately 30 minutes with 3 people. Insulated base and grounded tower configurations are available.

3-2.1.2 Top Hat. Due to the shortness of the tower relative to a quarter wave length antenna, top loading is essential. The top loading wires also serve as guys, supporting the tower during high wind conditions. The top hat assembly consists of 16 guys. Each guy includes an active radiator and an insulated section. For the design considered, the guy extends to a point on the ground twice the height of the tower. The active portion of the guy extends to a point directly above the end of a ground plane radial. For the 60 meter tower, the overall guy length is 135 meters which includes the active length of 75 meters and the insulated length of 60 meters.

The quantity of guys and dimensions of the active elements are based upon the design requirements for making the effective electrical height of a top-loaded vertical radiator equal to the actual height of the vertical structure. This is discussed in Section 2-2.1.3.

3-2.1.3 Antenna Coupler. The antenna coupler matches the impedance of the transmitting antenna to the transmitter power amplifier output. The coupler is an inductor tuning coil and uses coil tap selection for antenna tuning and transmitter feed connection. The physical parameters of the coil depend upon the operating frequency and height of the tower.

The tuning coil for the 30 meter tower configuration contains 200 turns of 0.64 cm copper tubing. It is 2 meters in diameter and 4 meters in height. For the 60 meter tower the coil contains 150 turns of 0.95 cm tubing. The coupler is installed in a van trailer for mobility and environmental protection. An RF feed-through bushing exists at the top surface of the trailer for connection to the antenna terminal.

3-2.1.4 Ground Plane. A ground plane is included to reduce the near-field ground system losses. The ground plane consists of 60 radials placed every 6 degrees around the tower base. Ground rods, 1.8 meters in length, terminate the radials and improve the electrical connectivity with the earth. At the tower base, the radials are interconnected and terminated with a ground rod. The radials are of 10 gauge copper wire. For evaluation, the radial length is equivalent to the tower height (30 and 60 meters).

3-2.2 Multiple Tuned Umbrella Arrays[3-1, 3-2]

A significant advancement in the performance of a physically and electrically short VLF/LF transmitting antenna was accomplished by the Rome Air Development Center (RADC), in the early 1970's. The objective of their effort was to develop a transportable VLF/LF antenna system which utilizes the mutual coupling effect of several radiation elements to improve system performance.

3-1 Ray, H.A., "Dispersible Transmitting Antenna VLF/LF Investigation" RADC-TR-72-28, Continental Electronics Manufacturing Co., March 1972.

3-2 Ray, H.A., "Experimental Model Dispersible Transmitting Antenna VLF/LF" RADC-TR-73-5, Continental Electronics Manufacturing Co., January 1973.

The initial design goals specified:

- o Mobility,
- o Tower heights not to exceed 30 meters, and
- o Radiated power of 250 watts minimum (0.5% efficiency).

The RADC antenna consists of four major functional components: 1) support towers, 2) antenna element top hat (umbrella), 3) tuning coils, and 4) ground plane. The physical configuration, referred to as a Multiple Tuned Umbrella Array, is shown in Figures 7 and 8.

3-2.2.1 Towers. Seven towers are used to support the top hat. The towers utilized in the RADC design are ROHN model number 55G sectional towers. Tower selection was based upon factors which included tension and compression in each leg and the ability to withstand specific wire and ice loads.

The guys supporting the tower are insulated at the top. The bottom ends are connected to ground potential to avoid inducing high voltage on an electrically floating section.

Erection of the sectional towers is time consuming. In a field demonstration, it was found that a crew of six required 10 days to initially erect the complete antenna. This time could be reduced with crew training and proficiency. The transportable telescopic tower described previously in paragraph 3-2.1.1 is an alternative that could be utilized to reduce the crew size and/or set up time to four men and approximately one day.

3-2.2.2 Top Hat. The top hat assembly employs three active wires in each of the three elements. These elements act as one plate of a capacitor with the other plate appearing at ground level. The quantity of wires in an element is a balance between the weight to be supported by the towers, the radiation efficiency and the conditions for corona onset on the wires.

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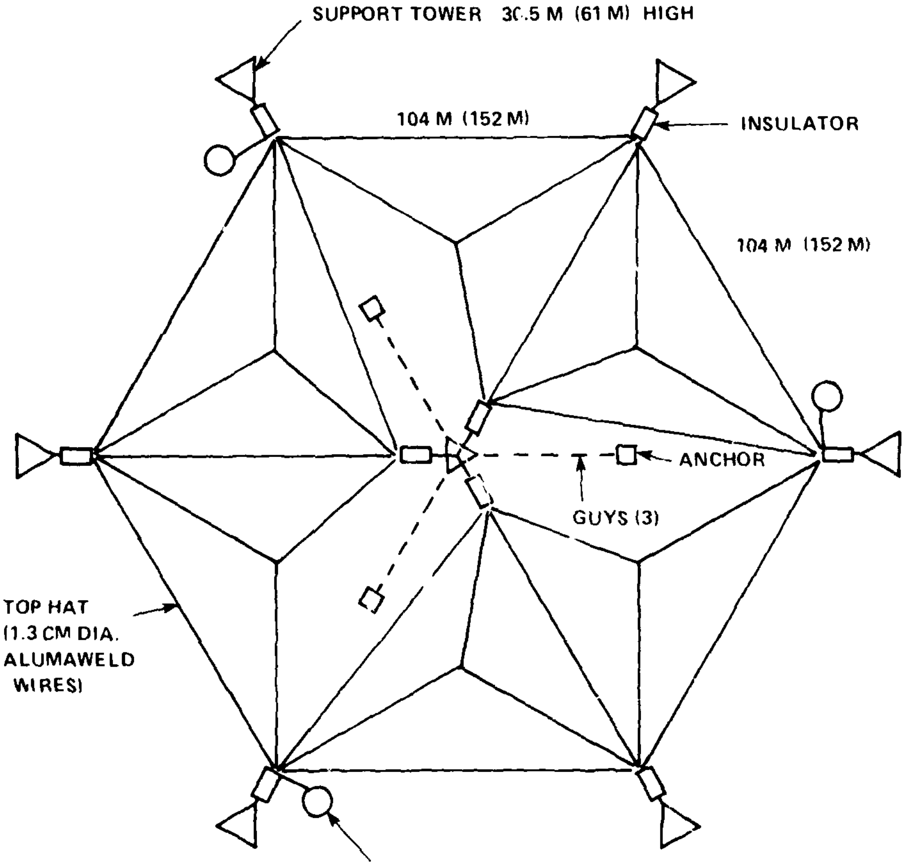
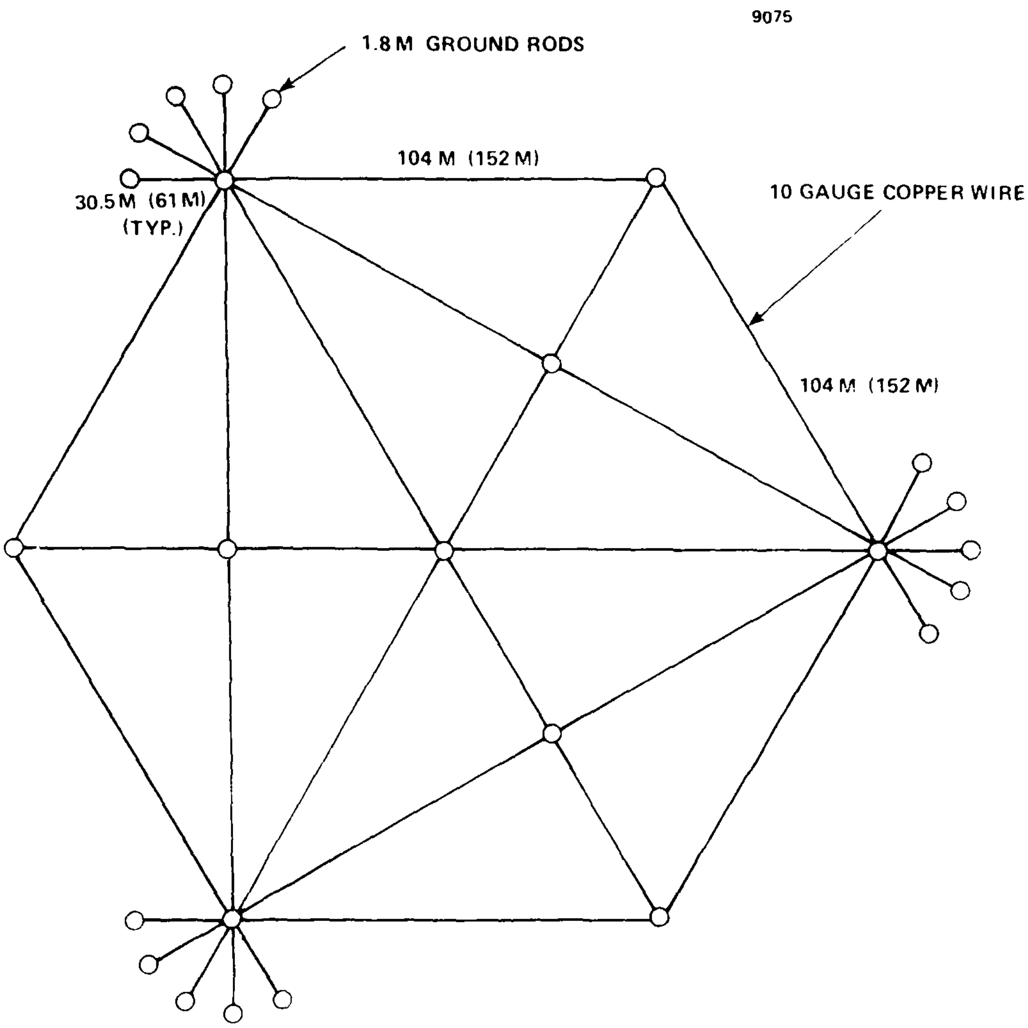


NOTE:

A. GUYS (9) AND GUY ANCHORS (3), HALYARDS (1) AND HALYARD ANCHORS (1) AT EACH PERIMETER TOWER NOT SHOWN.

B. DIMENSIONS SHOWN REPRESENT THE BASELINE RADC CONFIGURATION. THE DIMENSIONS IN PARENTHESES ARE THE ENHANCED CONFIGURATION.

Figure 7. RADC Multiple Tuned Umbrella Array - System Configuration



NOTE:

DIMENSIONS SHOWN REPRESENT THE BASELINE RADC CONFIGURATION. THE DIMENSIONS IN PARENTHESES ARE THE ENHANCED CONFIGURATION.

Figure 8. Multiple Tuned Umbrella - Ground Plane.

The top hat elements are insulated from the supporting towers. The top hat assembly is electrically connected to the loading coils by wires that are insulated from the tower structure.

3-2.2.3 Tuning Coils. Three tuning (loading) coils are used - one for each of the antenna elements. Each loading coil is effectively in series at the top of the tower, but is physically located at ground level. The tower is used for the low potential connection to the loading coil. The high potential side of the coil is connected to the top hat assembly by a wire insulated from the tower structure.

Each coil contains 120 turns of 1.0 cm outside diameter copper tubing. The coil is 1.2 meters wide by 1.8 meters high and is protected from the environment by a weatherproof enclosure.

Any of the coils can be used for transmitter feed connection. Dependent upon the operational frequency, the coil tuning and transmitter feed connections are accomplished by appropriate tap selection.

3-2.2.4 Ground Plane. The ground plane is a network of copper wire placed beneath the element wires of the top hat assembly in order to minimize near-field ground system losses. The wires are laid along the surface of the earth with driven ground rods at terminal and junction points. The ground plane network forms the bottom plate of the capacitor (the top plate being the top hat assembly). The wire arrangement and ground rod placement is shown in Figure 8.

3-2.2.5 Antenna Variations. Two versions of the Multiple Tuned Umbrella Array antenna are evaluated for performance in Section 3-3. These versions differ in the physical dimensions of the same basic configuration. This enables us to bound a range of antenna performance. One version is the "as-built" RADC antenna and is referred to as the baseline configuration. The second version considered is essentially

a doubled size of the "as-built" configuration and called the enhanced version. The towers are doubled in height and the top hat area is doubled. The physical dimensions of the two variations are indicated in Figures 7 and 8 where any dimension within parenthesis ( ) represents the enhanced configuration.

Associated with the enhanced configuration is a change in the quantity of guys needed for tower support. Each tower in the baseline configuration is supported at three levels by three equally spaced guys. The enhanced configuration requires a maximum of eight levels and is dependent upon the lengths of the individual tower sections.

3-3 ANTENNA PERFORMANCE

Both electrical and mechanical performance characteristics of the transportable tower configurations are derived using the methodology described in Section 2 and the configurations and physical parameters described in paragraph 3-2.

3-3.1 Electrical Performance

Profiles of radiation efficiency for the single tower antenna and the multiple tuned umbrella array are presented in Figures 9 and 10 respectively. Profiles of the 3dB system bandwidth for these same two transportable antenna configurations are given in Figures 11 and 12 respectively.

3-3.1.1 Radiation Efficiency. In Figure 9, the upper curve represents the radiation efficiency that can be achieved with a 60 m tower antenna while the lower curve represents the 30 m tower performance. It can be seen that by doubling the antenna tower height a fourfold improvement in radiation efficiency can be obtained.

In figure 10, the radiation efficiency of the Multiple Tuned Umbrella Array is presented. The lower curve of the range presented in this figure represents the performance (theoretically derived and substantiated by experimental results published in RADC reports)[3-1, 3-2] of the baseline "as-built" RADC antenna system. The upper curve represents the radiation efficiency achievable by doubling the tower height, the top hat area and ground plane in an enhanced version of the same configuration. Again, it can be seen that doubling the antenna height provides a factor of four increase in radiation efficiency.

When comparing radiation efficiencies between the single radiating tower and the multiple tuned array it is clear that the latter is more than four times as efficient. This result obtains from the fact that the radiation resistance of the multiple tuned antenna is more than two and a half times that of the single tower antenna. Since efficiency is proportional to the square of the radiation resistance this difference in radiation resistance amounts to a factor of seven increase in efficiency. However greater losses in the multiple tuned array reduce the overall efficiency to a net increase of about a factor of four.

3-3.1.2 System Bandwidth. The 3-dB system bandwidths for both 30m and 60m heights of the Single Tower and Multiple Tuned Umbrella Array configurations are presented in Figures 11 and 12, respectively. It can be seen that all four antenna configurations have approximately the same system bandwidth over the frequency range of interest. Assuming the requirement for approximately a 200 Hz bandwidth at 30 kHz, a nominal radiation efficiency of 0.07% can be achieved for a 30 meter single tower system. A 60 meter single tower system can achieve 0.58% efficiency. In contrast, 30 m and 60 m multiple tuned umbrella arrays could provide radiation efficiencies of 0.78% and 3.20% respectively while maintaining close to a 200 Hz 3dB bandwidth.

3-1 Ibid
3-2 Ibid

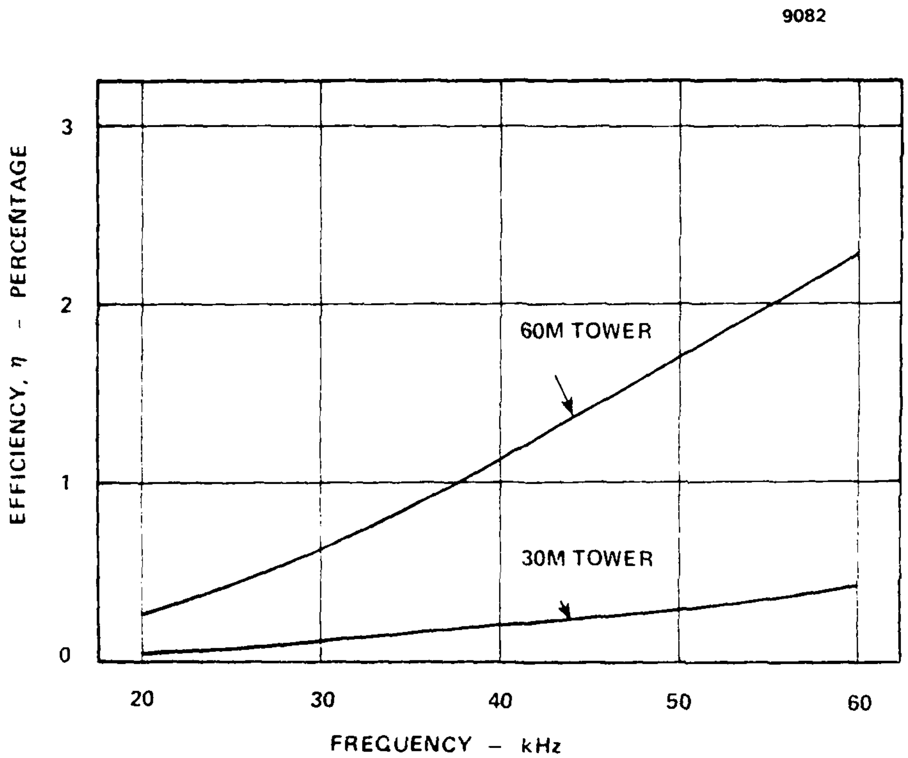


Figure 9. Single Tower Antenna - Radiation Efficiency.

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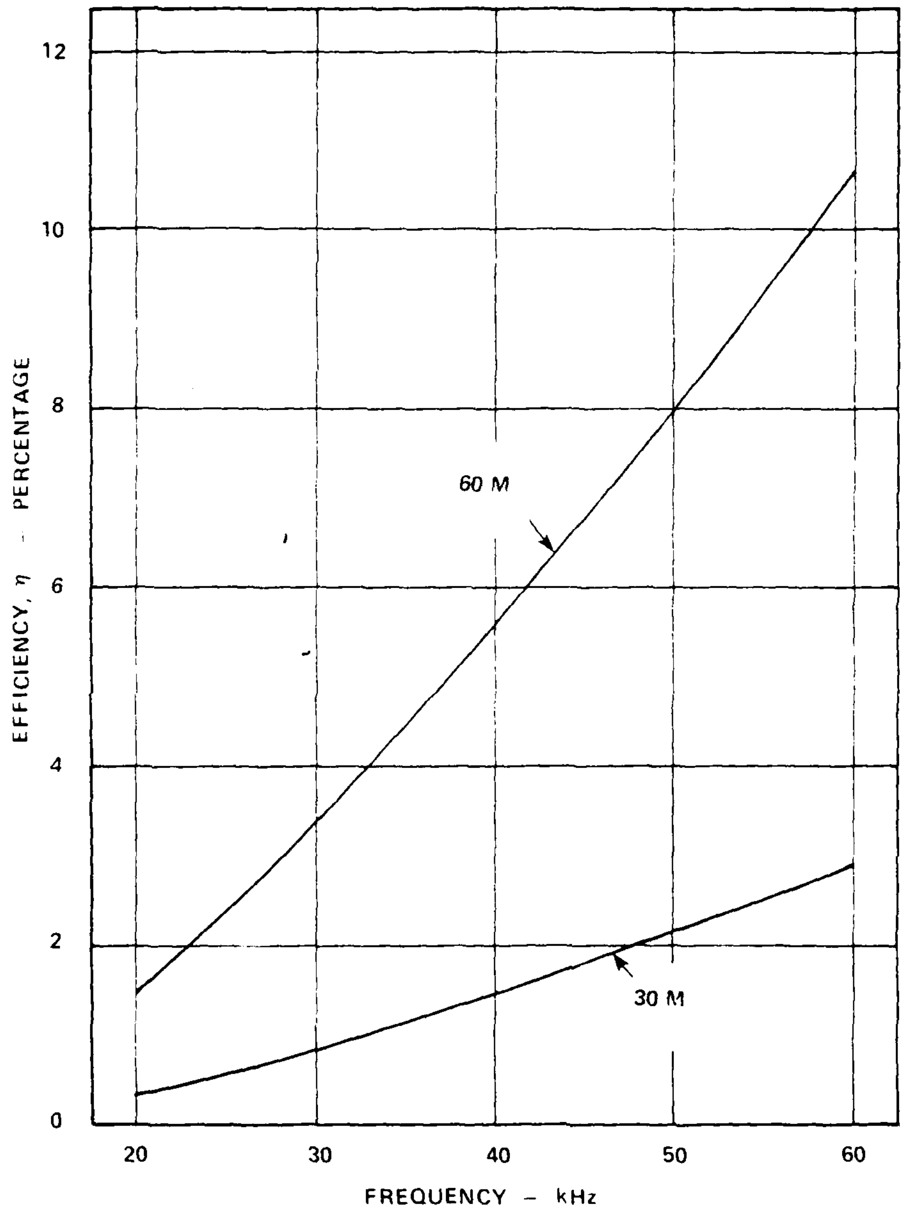

Figure 10. Multiple Tuned Umbrella Array - Radiation Efficiency.

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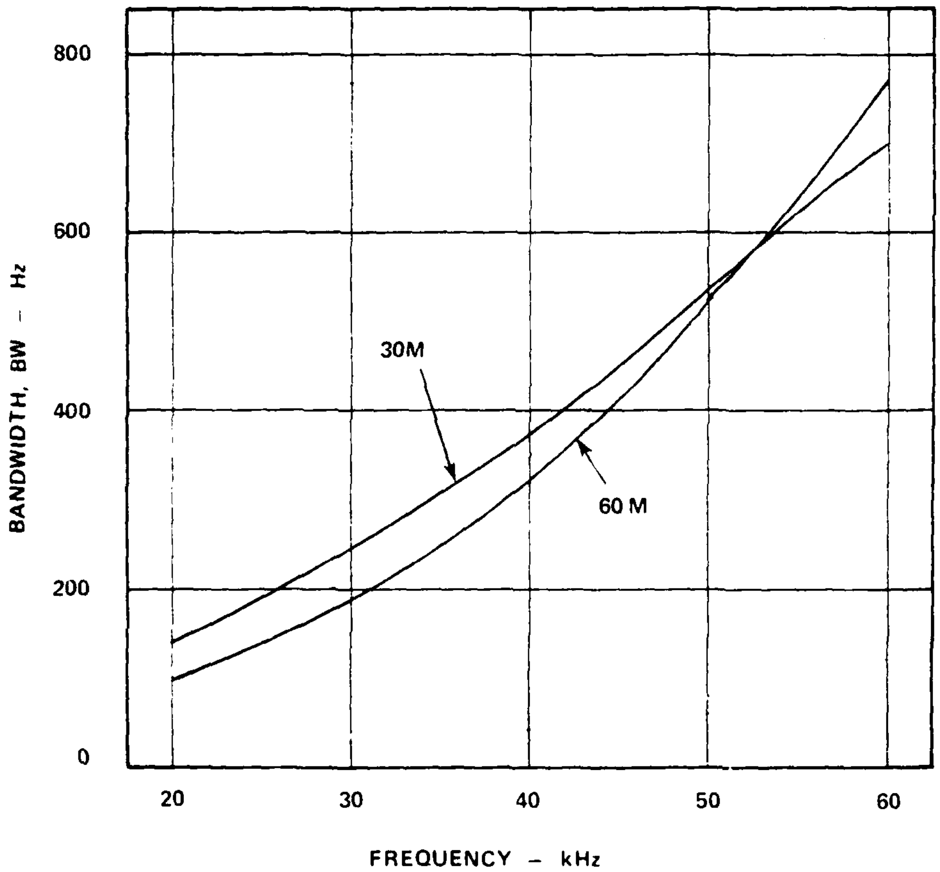

Figure 11. Single Tower Antenna - System Bandwidth.

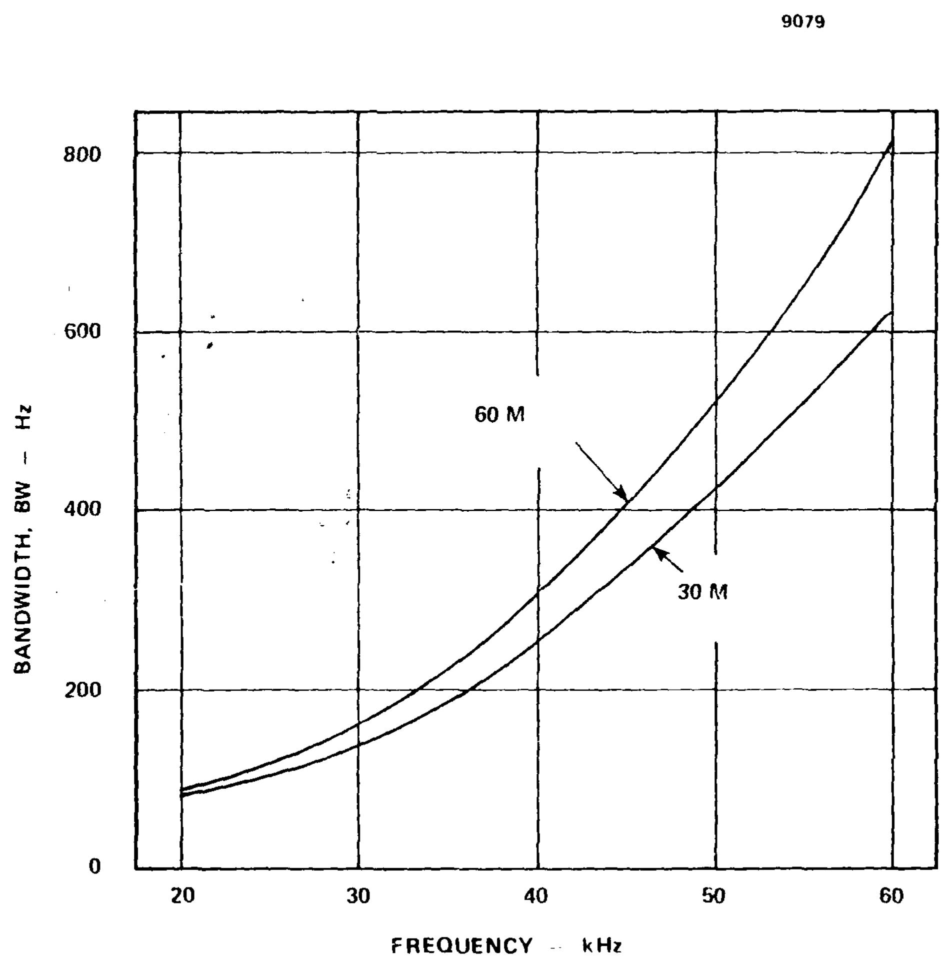

Figure 12. Multiple Tuned Umbrella Array - System Bandwidth.

3-3.2 Mechanical Performance

The same wire diameter and material that is used in the baseline Multiple Tuned Umbrella Array can be used in the enhanced version. From mechanical evaluation of the enhanced version, the aluminum wires have a safety factor of about 15.9 in normal environmental conditions. For environmental conditions of combined ice (0.75 cm ice build-up) and wind loading (100 km/hr) the safety factor is decreased to approximately 2.25.

3-4 DEPLOYMENT

3-4.1 Deployment Concept

The transportable tower antenna systems are intended to be completely mobile, antennas capable of being deployed with no advanced site preparation. The systems can be stored on or in their transport vehicles. The crew and antenna, as a unit, are deployed to a site location. At the site, the crew assembles the antenna and begins operation. Relocation is achieved by disassembling, transporting and reassembling the antenna.

3-4.2 Site Requirements

Either configuration of the transportable tower configurations has similar site requirements. The site must be relatively level and free of obstructions which would impair assembly and set-up of the antenna. Rough terrain is acceptable provided the ground plane can be deployed and guy wires placed. The soil should be sufficiently firm to support the towers and to hold the guy anchors in place. Selection of a site should avoid terrain which is too soft (swamp, loose fill, etc.) or too hard (solid bed rock, dense clay or gravel, etc). The immediate area surrounding a tower base should be flat and level. The minimum site area required must not only accommodate the antenna including outlying guy

anchors, but must also include sufficient area for maneuvering of the set-up vehicles. Minimum site dimensions for the transportable tower antenna configurations are 14,400 and 57,600 square meters (3.5 and 14 acres) for the two versions of the single tower antenna (30 and 60 meters high, respectively) and 56,600 and 133,000 square meters (14 and 33 acres) for the baseline and enhanced versions of the Multiple Tuned Umbrella Array.

3-4.3 Installation and Set-up

The installation and set-up process for the two configurations of the transportable tower antennas are significantly different and are treated separately in the following paragraphs.

3-4.3.1 <u>Single Tower Antenna</u>. In its transport stored position, the nested telescopic tower rests on trailer racks just above the erection winch as illustrated in Figure 13. The trailer is stabilized by extending outrigger arms and is then leveled. The nested tower is cranked from a horizontal to a vertical position as illustrated in Figure 14, with the base of the tower at the rear of the trailer. Either a manual or motorized cranking system may be used. The base section of the tower is secured to the trailer body. The Tri-Ex tower is designed such that the remaining tower sections are raised in the nested position. Each section is locked in place and guyed as it is extended and avoids the need to fully extend the tower before securing the guys. The tower sections are self-locking so that each section locks into place when it is fully extended. All locking arms are spring loaded and can be controlled from the ground. The uppermost level of guys are the top hat elements. The guys are secured to screw anchors.

When the tower has reached its full extension, as shown in Figure 15, all guys must be tightened, starting with the lowest guy assembly and proceeding through each assembly in turn to the top guy assembly.

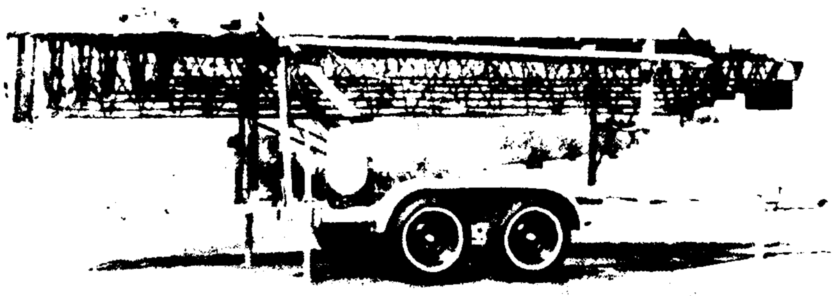

Figure 13. Tri-Ex Tower - Transport Configuration.

Figure 14. Tri-Ex Tower - Initial Set-Up Configuration.

The ground plane system is contained on 60 spools - one for each radial. Each radial is installed approximately every 6 degrees around the base of the tower with the radial ends secured to ground rods. The tuning coil can can now be brought alongside the tower trailer and the transmission line connected.

Installation and set-up for the two single tower antenna versions are estimated to require 34 man-hours for a 30 meter version and 40 man-hours for the 60 meter version. A significant portion of the difference between man-hours for each version is attributed to the increased length of the ground plane radials. Doubling the length of a radial increases the estimated man-hours for radial installation by a factor of 2.

A crew size of , people should be adequate to install and set-up either version of the single tower antenna configuration. No additional or special construction equipment is required.

3-4.3.2 Multiple Tuned Umbrella Array. The Multiple Tuned Umbrella Array involves a significantly different installation and set-up approach than the single tower configuration described in 3-4.3.1. The Multiple Tuned Umbrella Array is based upon a design developed by RADC. This design utilizes sectionalized towers which requires more equipment and man-power to set-up. An alternative to the sectional tower is the telescopic tower discussed previously. The installation and set-up processes for both approaches are discussed below:

Sectionalized Tower

To erect the antenna having 30 meter sectionalized towers, the location for each tower and the guy anchor placements must first be marked. Then screw type anchors for the guys and halyards are installed. The towers are assembled on the ground with the perimeter towers directed to the center of the array and with all guy wires attached. The towers are raised using a gin pole and tow vehicle. Control of the towers as they are raised is accomplished with the guys. When the towers are vertical, the guys are attached to the anchors, the towers plumbed and the guys tensioned.

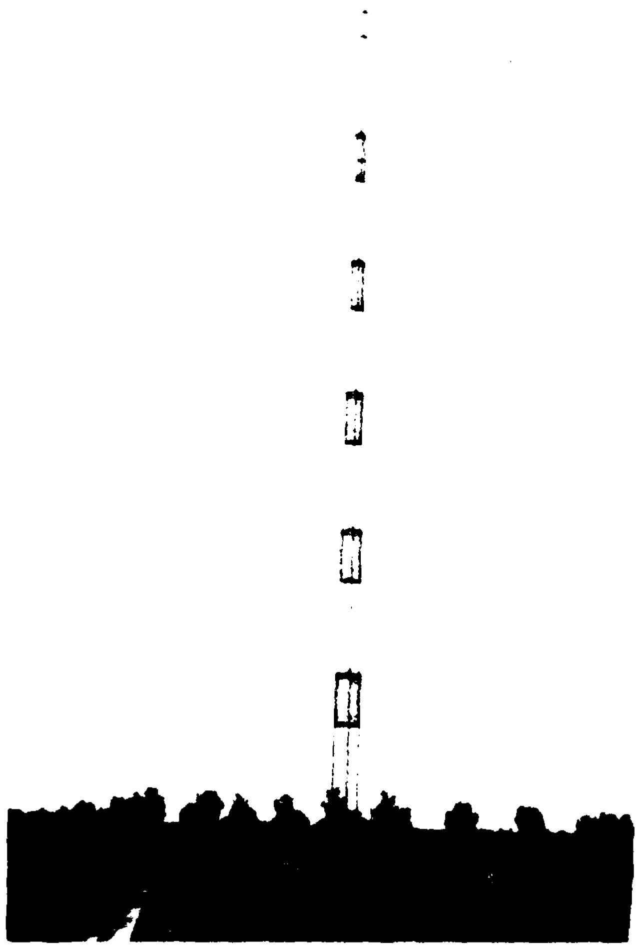

Figure 15. Tri-Ex Tower - Full Extension Configuration.

To erect the antenna having 60 meter sectionalized towers, two approaches can be used to set-up the towers. The easiest and quickest approach is to use a crane. With a crane, the complete tower can be assembled while on the ground. The crane would lift the assembled tower into place and support it while the guys are attached and secured to the ground anchors.

If a crane is not available, the other approach, which uses the gin pole technique, is used. With the gin pole technique, the tower must be installed in sections. The first section installed would be a 30 meter section and is set-up in the same manner as the 30 meter tower. The remaining 30 meter section will require installation in subsections of 5 meter increments. For each 5 meter subsection the gin pole is moved up the installed tower to enable the subsection to be raised and bolted into place. Every other subsection requires a level of guy wires for structural support. The 60 meter tower can require a maximum of 8 levels of guys dependent upon the lengths of individual sections. The increased height will also require a second set of anchors per tower.

Installation and set-up of sectionalized towers requires a minimum crew size of six people. Three people are needed for guy wire control, one person to operate the tow vehicle and two riggers on the tower to bolt on the new section and to raise the gin pole to the next level for another lift of a new section. After the 30 meter base section is in place the tow vehicle operator can be used to rig new sections to the wire hoist.

<u>Telescopic Tower</u>

To erect the antenna system which uses telescopic towers, the procedure described in paragraph 3-4.3.1 is used for each tower. The seven trailers are parked, outrigged and leveled in the appropriate tower locations.

Top Hat and Other Antenna Components

For the antenna which use sectionalized towers, the top hat array is assembled on the ground. The inside corners of the top hat are raised to the top of the center tower using the tow vehicle, and the appropriate connections are made atop the tower. The outside corners are then raised at the perimeter towers. The top hat is raised halfway at each tower in sequence, and then to the top. Final tensions are set in the halyards and final electrical connections are made.

If the antenna system uses telescopic towers, a different approach for top hat installation can be used, but requires the towers to be in their vertical nested configuration. The top hat would be connected to the towers before any tower extension in accomplished. After the top hat is installed, each tower is extended one section at a time beginning with the center tower and sequencing around the perimeter towers until the towers are fully extended and guyed. At this time, the final tensions and electrical connections can be made.

The ground plane, in its stowed configuration, consists of 8 spools of wire and 25 ground rods. Installation of the ground plane involves unwinding each spool of wire along the ground wire path between towers and to the extension points beyond the towers with tuning coils. Wire ends and wire crossover points are clamped to ground rods driven into the earth.

Each of the three tuning coils are placed beside the designated towers and are connected electrically to the tower and top hat element.

3-4.4 Transportation

The method for transporting the transportable tower configurations is dependent upon the tower design utilized. The Tri-Ex telescopic tower is supplied with an integral trailer which serves to both transport and set-up the tower. The sectional tower requires a van

type trailer for transport. For the baseline Multiple Tuned Umbrella Array, the entire antenna using sectional towers can be transported in two 2.5 meter high, 9.2 meter long, 10 metric ton vans. The enhanced version with sectional towers, requires twice as many vans.

If the Tri-Ex towers are used in the Multiple Tuned Umbrella Array the vehicle requirements change to seven trailers and one van. The van is used for transport of the tuning coils, top hat elements and ground plane components.

3-4.5 Summary of Deployment Parameters

A summary of the site requirements, installation and set-up parameters and vehicle requirements for the different versions of the transportable tower antennas is provided in Table 1.

3-5 COST ASSESSMENT

This section addresses the cost of procurement of the two different configurations of the transportable tower antennas. For the Single Tower configuration, costs are developed for versions with towers of 30 meter and 60 meter heights. The costs for the Multiple Tuned Umbrella Array configuration are also developed for these same two tower heights. In addition, costs are further developed for systems using a sectional tower and telescopic tower.

3-5.1 Assumption/Methodology

With the exception of the baseline Multiple Tuned Umbrella Array configuration using sectional towers, cost estimates include the requirement for a Research, Development, Test and Engineering (RDT&E) effort. It is assumed that no further RDT&E is required for the baseline Multiple Tuned Umbrella Array. Total acquisition costs, therefore, include RDT&E (if applicable) and production costs. The total acquisition costs are developed for a single antenna procurement and for

Table 1

TRANSPORTABLE TOWER SYSTEM - DEPLOYMENT SUMMARY

Deployment Parameter	Single Tower System		Multiple Tuned Umbrella Array				
			Baseline		Enhanced		
	30m	60m	Sectional Tower	Telescpoic Tower	Sectional Tower (w/crane)	Sectional Tower (w/gin)	Telescopic Tower
Site Requirements (minimum)							
Site Dimensions (m)	120x120	240x240	240x240	240x240	365x365	365x365	365x365
Total Site Area (m^2)	14,000	57,600	57,600	57,600	133,000	133,000	133,000
Installation and Set-up							
Erect Towers (man-hours)	1.5	2.0	356 (1)	22.5 (1)	356.0 (1)	516.0 (1)	29.0 (1)
Install Guy Anchors (man-hours)	19.0	22.0	21	21.0	40.0	40.0	40.0
Install Ground Plane Wire (man-hours)	2.5	5.0	1.5	1.5	3.0	3.0	3.0
Install Ground rods (man-hours)	10.0	10.0	3	3.0	3.0	3.0	3.0
Install Top Hat (man-hours)	- (2)	- (2)	12	3.0	18.0	18.0	4.0
Total Man Hours	33.0	39.0	393.5	51.0	420.0	580.0	79.0
Minimum Crew Size	6	3	6	6	6	6	6
Transport Vehicles							
Tower Trailer	1	1	-	7	-	-	7
Coupler Van	1	1	-	-	-	-	-
Van - Large Size	-	-	2	-	4	4	-
Van - Medium Size	-	-	-	1	-	-	1
Van - Small Size	1	1	-	-	-	-	-

NOTES:

(1) Includes Time Required to Survey and Locate Tower Positions
(2) Man-Hours Included in Tower Erection

incremental procurements of up to eighty (80) antennas of the same configuration. This can be extended further recognizing that unit costs decrease as production quantities increase. The total acquisition costs estimated for the various transportable tower antennas are presented in Figure 16.

3-5.2 Single Tower Antenna Cost

Two variations of the single tower antenna are considered. Either variation requires a Full Scale Engineering Development to refine component design for VLF/LF application. The cost differences between the two variations are due primarily to differences in the cost of materials. The procurement cost for a single 30 meter antenna is $1,176K. The total acquisition costs are shown in Figure 16 as a function of the quantity of antennas acquired where the cost includes the production units plus the RDT&E unit. It is estimated that delivery of the antenna for either height would take place approximately 16 months after contract award.

3-5.3 Multiple Tuned Umbrella Array

The acquisition costs for the Multiple Tuned Umbrella Array are based upon the RADC antenna. Costs are presented for both the baseline and enhanced version with two different tower designs. One design used Rohn sectionalized towers and the other used Tri-Ex telescopic towers. As noted previously, RDT&E costs are not incurred with the baseline system using sectionalized towers.

The acquisition costs and anticipated delivery times for a single antenna procurement are summarized below.

Baseline Antenna Procurement Costs		Delivery
Antenna with Sectionalized Towers	- $340 K	12 mo.
Antenna with Telescopic Towers	- $500 K	12 mo.
Enhanced Antenna Procurement Costs		
Antenna with Sectionalized Towers	- $1,770 K	24 mo.
Antenna with Telescopic Towers	- $1,810 K	24 mo.

Total acquisition costs for incremental antenna procurements are presented in Figure 16.

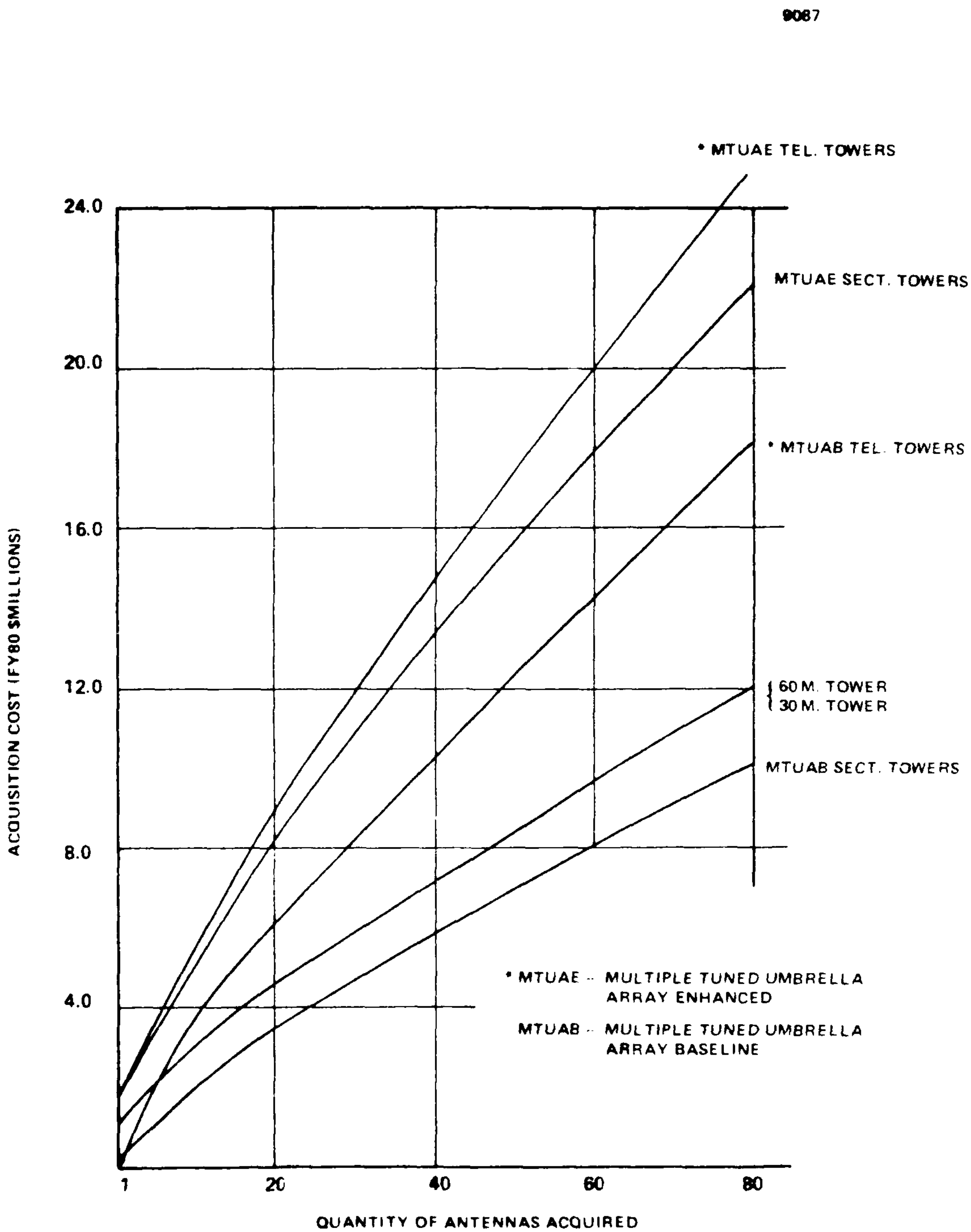

Figure 16. Total Acquisition Cost (RDT&E and Production) Transportable Tower Antennas.

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LEGEND:

I. SINGLE TOWER ANTENNA
  1. 30 M TOWER
  2. 60 M TOWER

II. MULTIPLE TUNED UMBRELLA ARRAY
  1. BASELINE
    A. W/ SECTIONAL TOWERS
    B. W/ TELESCOPIC TOWERS
  2. ENHANCED
    A. W/ SECTIONAL TOWERS
    B. W/ TELESCOPIC TOWERS

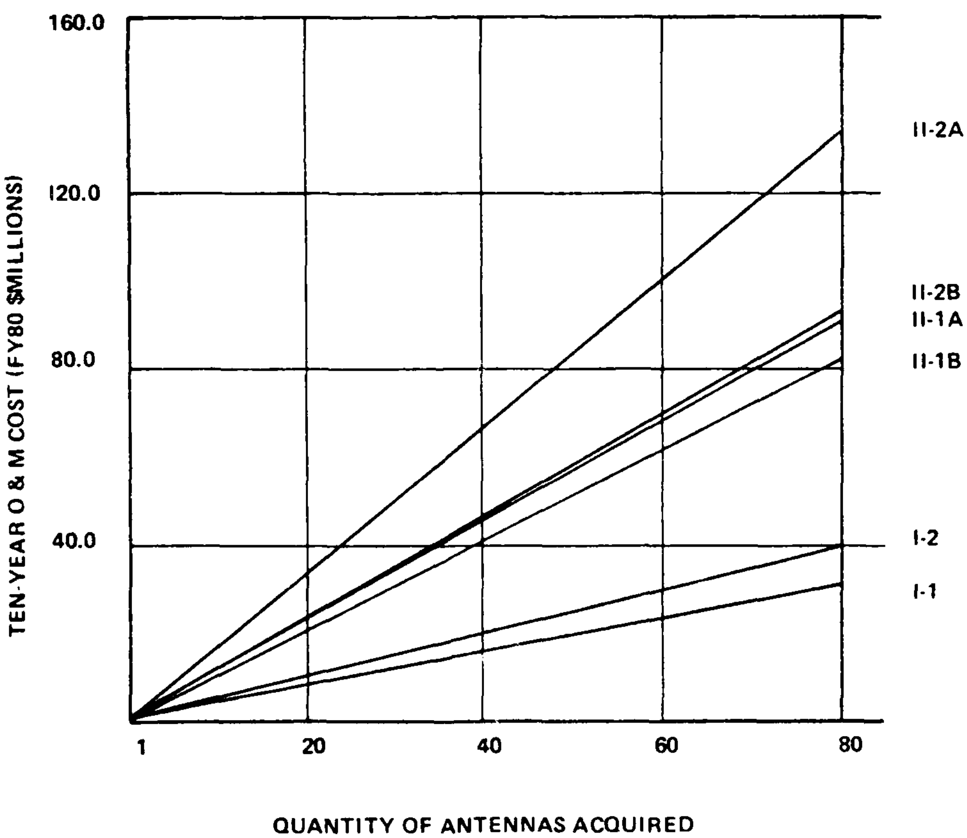


Figure 17. Total O & M - Transportable Tower Antennas.

SECTION 4
FIXED LOCATION TOWER ANTENNAS

4-1 INTRODUCTION

In a paper prepared by Mr. R.F. Schulz[(4-1)], a suggestion was made to use the growing quantity of towers in the 300 to 600 meter range for a dual purpose--namely, normal radio or television broadcast and emergency low frequency communications. In existence within the continental U.S. and randomly distributed east of the Rocky Mountains are 400 towers with heights between 180 and 250 meters; 250 with heights between 250 and 300 meters; 240 with heights between 300 and 370 meters; and 200 above 370 meters.

By modifying a large quantity of such towers to enable VLF/LF transmissions, the redundancy of available ground-based transmitters can potentially provide a degree of system survivability. As an additional benefit, the cost for modifying a tower already in existance should be considerably less than the cost to design and install a new tower antenna dedicated solely for VLF/LF.

The performance improvement of fixed location tower antennas can be one or two orders of magnitude better than that of the low profile transportable tower configuration discussed in Section 3. Tower systems 300 meters in height can achieve radiation efficiencies of up to 50% at 30 kHz. Systems 600 meters in height can achieve efficiencies of nearly 80% at the same frequency.

The degree of performance that can be achieved by a fixed location tower antenna is constrained by specific site parameters which limit the modification that can be made to an existing antenna system.

[(4-1)] Schulz, R.F., "The Use of Existing Structures as LF Antennas," SRI International, February 1979.

These parameters include the available land area immediately surrounding the tower for ground plane installation, the distance from the tower base that guy anchors are placed and the load that the tower can support.

In general, most TV antenna towers are grounded (i.e., the tower is not insulated at the base). Guy anchors are placed a distance nominally 35% of the tower height from the base of the tower. Accounting for the effects of combined icing and wind, the tower system has a safety factor of approximately 2.5 which limits the amount of additional load that can be added to the system.

Site-to-site and antenna-to-antenna variations exist which affect the design of a tower modification and the performance that can be achieved. Each antenna installation is unique. Therefore, ranges of performance are considered to cover most possible combinations of these variations.

There are three distinctly different approaches available to convert an existing radio or television broadcast tower into a dual purpose system. One approach is to insulate the tower from ground with a base insulator (<u>insulated base tower</u>) and enable the tower to be used as a vertical radiator. This approach is not evaluated further due to the need to completely dismantle the tower to install a base insulator and to replace all guys with longer and insulated versions. The nominal cost to dismantle the tower, install the base insulator and erect the tower with a new guy system is $1 M for a 300 meter tower. A 600 meter tower can cost $1.5 M. The cost alone warrants investigating other alternatives which avoid the need to install a base insulator.

A second approach utilizes shunt-feed techniques (<u>shunt-fed tower</u>). This approach requires the replacement of all guys. All but one of the new guys are insulated from the tower at the lower levels. The top level of guys are used as a "top hat" to the tower and are electrically connected to the tower but insulated from the ground anchors. The lower uninsulated guy at a height of approximately one fifth of the tower height is used to complete a one turn inductance

antenna circuit consisting of the guy, tower and ground return. Shunt-fed techniques can be applied to 600 meter grounded towers with operating frequencies as low as 100 kHz with minimal difficulty. At lower frequencies and for shorter antenna towers it is extremely difficult to obtain a reasonable resistance component at the terminal of the feed guy unless the feed guy is connected to the tower at an excessive height above ground. In fact, shunt excitation is not practical when the antenna height is much less than 0.2 wavelengths. Consequently, this approach is not evaluated in this report.

A third approach is a radiating guy tower. This approach minimally affects the existing tower configuration. The tower does not require a base insulator nor do all guy wires require replacement. Only the top-most level of guys are affected. Involved is a new set of guy wires insulated from both the tower and ground. The guys are electrically interconnected at the tower top. The lower active portion of one guy is connected to the antenna coupler terminal.

The radiating guy tower configuration is evaluated further in this section. Fixed location towers are vulnerable to targeting and nuclear blast effects. This factor must be considered further and is discussed in deployment (paragraph 4-4). Associated costs for variations in the modificaton to such towers are presented in paragraph 4-5.

4-2 ANTENNA DESCRIPTION

The physical and component characteristics for the radiating guy tower configuration are examined. Considered also is the variation of site parameters that may exist at individual antenna locations. In particular, the available land area surrounding the tower base governs the lengths of the ground plane radials that can be placed. A significant variable is also the locations of the guy anchors for the tower.

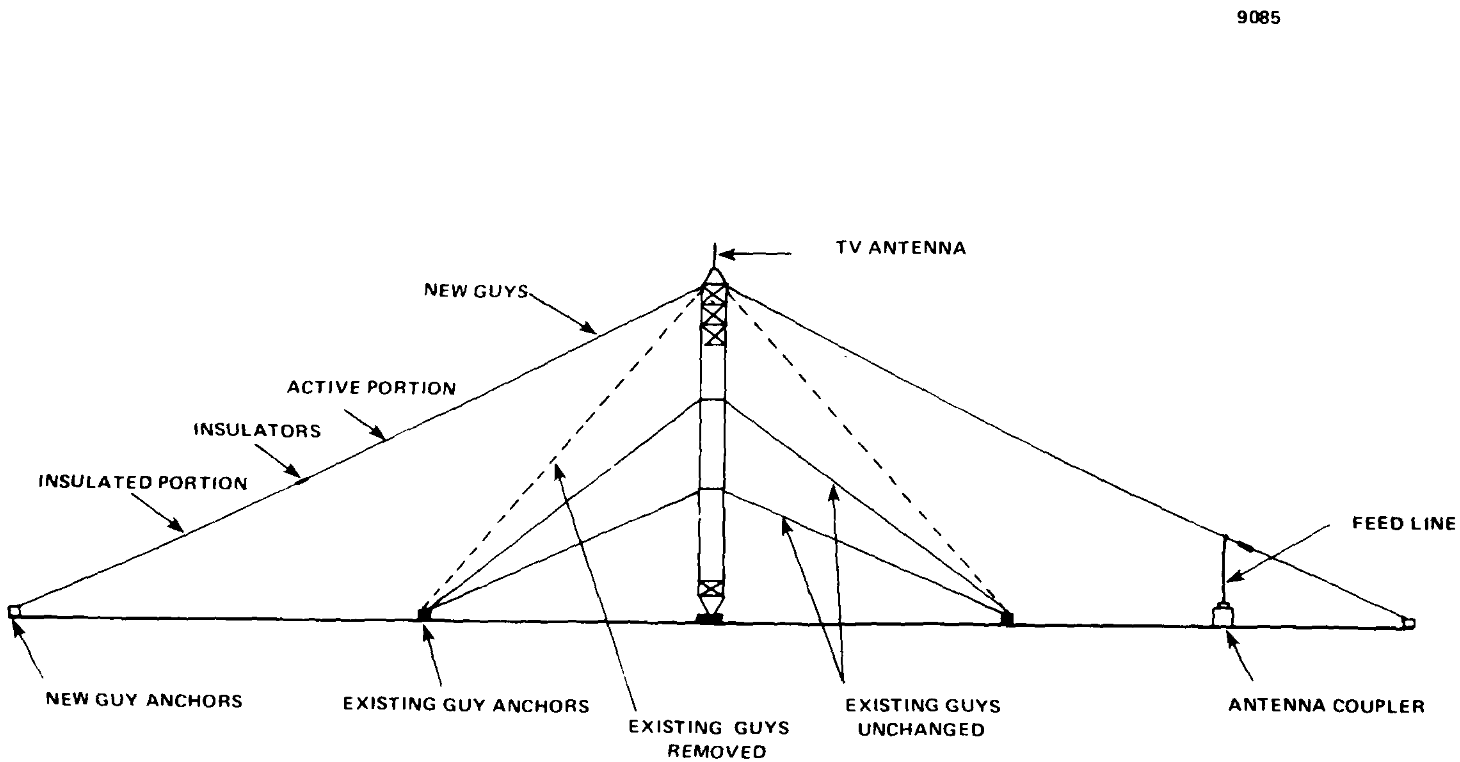


Figure 18 Radiating Guy Tower - Side View.

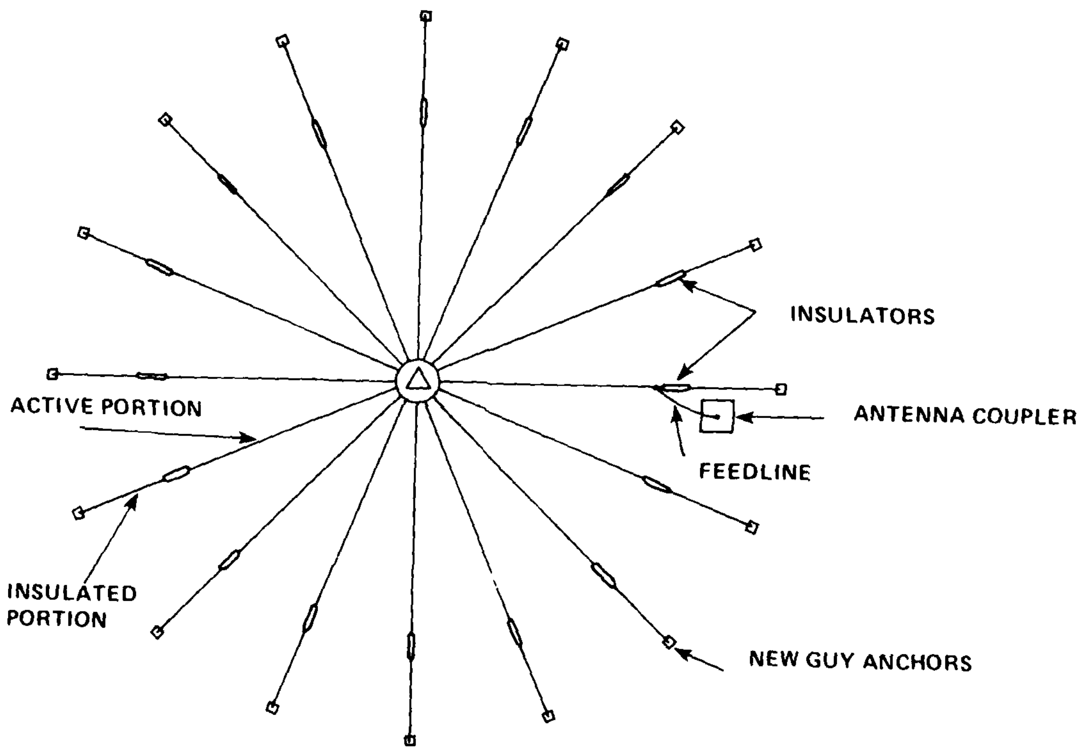


Figure 19 Radiating Guy Tower - Top View

Figures 18 and 19 represent the physical configuration of the radiating guy tower system that is evaluated. The physical parameters considered during evaluation are described in the component descriptions that follow. For evaluation, the earth conductivity of the site is assumed to be within the range of 10^{-3} to 10^{-2} mhos/meter.

4-2.1 Tower

The tower serves as the supporting structure to the radiating guy network. No changes are made to the tower except at the top where the new radiating guy system is attached. The addition of these guys should not affect normal operation of a television broadcast station. There may be mutual coupling effects introduced at a radio broadcast station which uses the tower as the radiating element. This would require further assessment and is not considered in this evaluation. For evaluation tower heights of 300 and 600 meters are considered.

4-2.2 Guy Wire System

A major portion of the modification to an existing tower system is associated with the guy wires. Involved is the removal of the top-most set of guy wires. These guy wires are replaced with a new guy wire system. Each new guy wire contains an active and insulated portion. For evaluation, two ratios of active length to total guy length are considered. One ratio assumes the active length to be half of the total length (0.5). The other ratio assumes a relationship of 0.8. The new guy system contains 16 wires for evaluation. The quantity can be increased or reduced, as desired, but dependent upon the structural capability of the tower to support the weight of the guy system. Of concern is the capability of the tower to support the weight of the top hat assembly considered. No variations of the top hat assembly other than the two aforementioned chord length ratios are considered for further evaluation.

New guy anchors are required for the guy wire system. For evaluation, the guy anchors are located a distance twice the tower height from the base of the tower.

Each guy wire in the system is electrically interconnected at the top of the tower by a bonding strap arrangement.

4-2.3 Antenna Coupler

For evaluation the antenna coupler is included with each site modification and is permanently installed at the site. This assumption is based upon the site-to-site variations that can be encountered which requires a time consuming antenna tuning process.

The tuning coil is installed in an environmentally controlled, RFI shielded building with an RF bushing located at the top of the building. Electrical connection to an active guy wire is made from this bushing. Litz wire is used to construct the tuning coil. The tuning coil is two meters in diameter and four meters in height. Due to the variation of antenna and site parameters, the number of turns in the tuning coil can vary in a range of 40 to 70 turns. Antenna tuning and transmitter connection is achieved by tap connection to the appropriate turn.

4-2.4 Ground Plane

Although not shown in Figures 18 or 19, installation of a ground plane is included as a part of the site modification. For purposes of evaluation, two distinct ground plane configurations are investigated. The first of these is a ground plane consisting of a wire mesh grid with a grid spacing of approximately 0.1 meters. The grid would have a diameter of 10% of the tower height and would completely encircle the base of the tower. The second ground plane configuration would be considerably larger. It consists of a wire mesh grid, identical to the one just described, to which is connected a set of 180 wires

extending radially outward from the base of the tower. The length of these wires would be 90% of the tower height such that the radius of the entire ground plane would be equal to the height of the tower.

4-3 ANTENNA PERFORMANCE

System performance that can be obtained by modifying existing TV antenna structures is presented in this section. System performance is related to tower height, the top hat assembly radius, the ground plane radius and the earth conductivity of the antenna site.

4-3.1 Electrical Performance

Electrical performance profiles are developed for tower heights of 300 and 600 meters. Radiation efficiency profiles are presented in Figures 20 and 21. System Bandwidths are presented in Figures 22 and 23. The inter-relationships between these parameters are discussed in greater detail in the following paragraphs.

4-3.1.1 Radiation Efficiency. There is a significant improvement in the radiation efficiency of towers in the 300 to 600 meter range in comparison to the 30 and 60 meter single tower antennas described previously in Section 3. There is also a significant improvement in the radiation efficiency performance at lower frequencies (less than 30 kHz) for 600 meter towers in comparison to 300 meter towers.

Radiation efficiencies are based on top hats comprised of 16 active guys. The efficiencies shown in Figures 20 and 21 are parametric in top hat (active guy) chord length, ground plane radius and earth conductivity. Using two values for each parameter, as indicated in Table 2, results in the eight curves for each tower height. Use of fewer active guys dramatically reduces the efficiency of the grounded tower as a radiator.

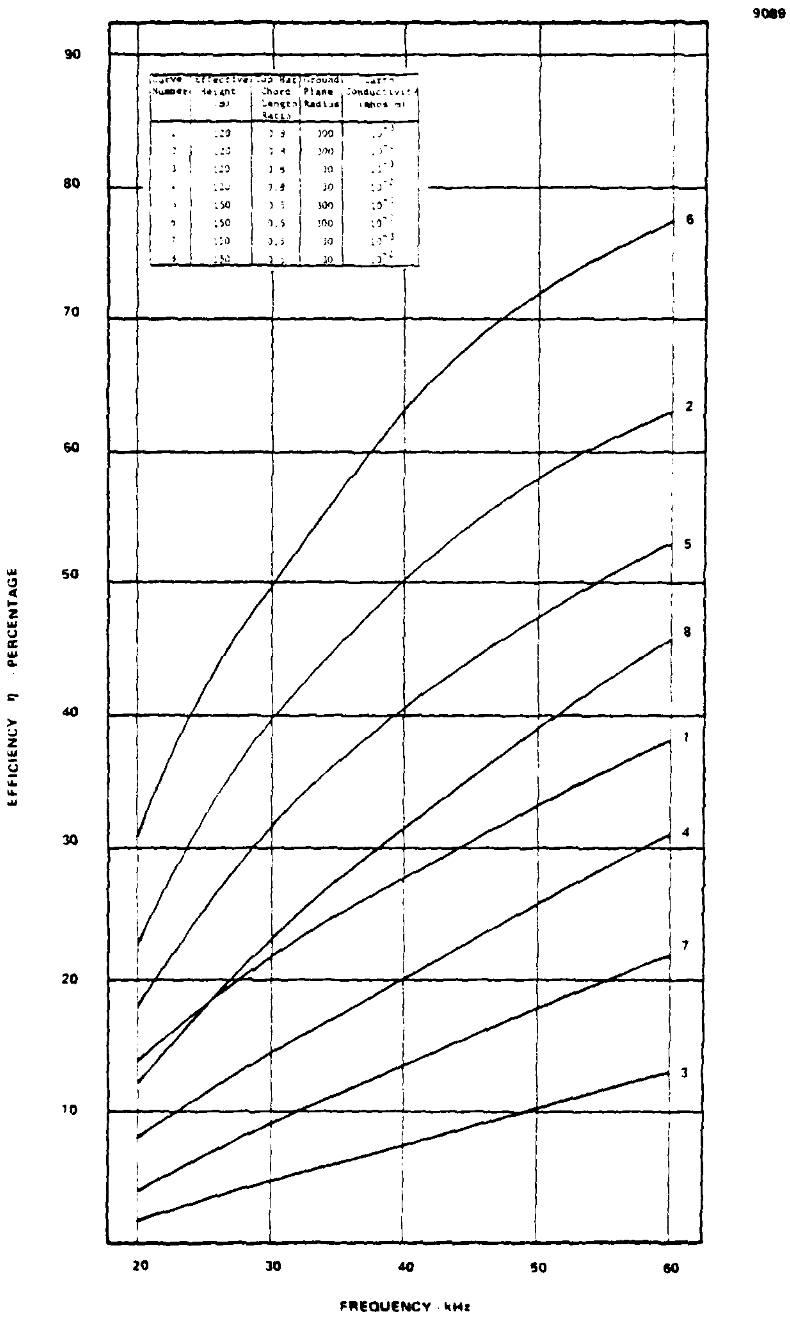


Figure 20.   300 meter Tower Systems - Radiation Efficiency.

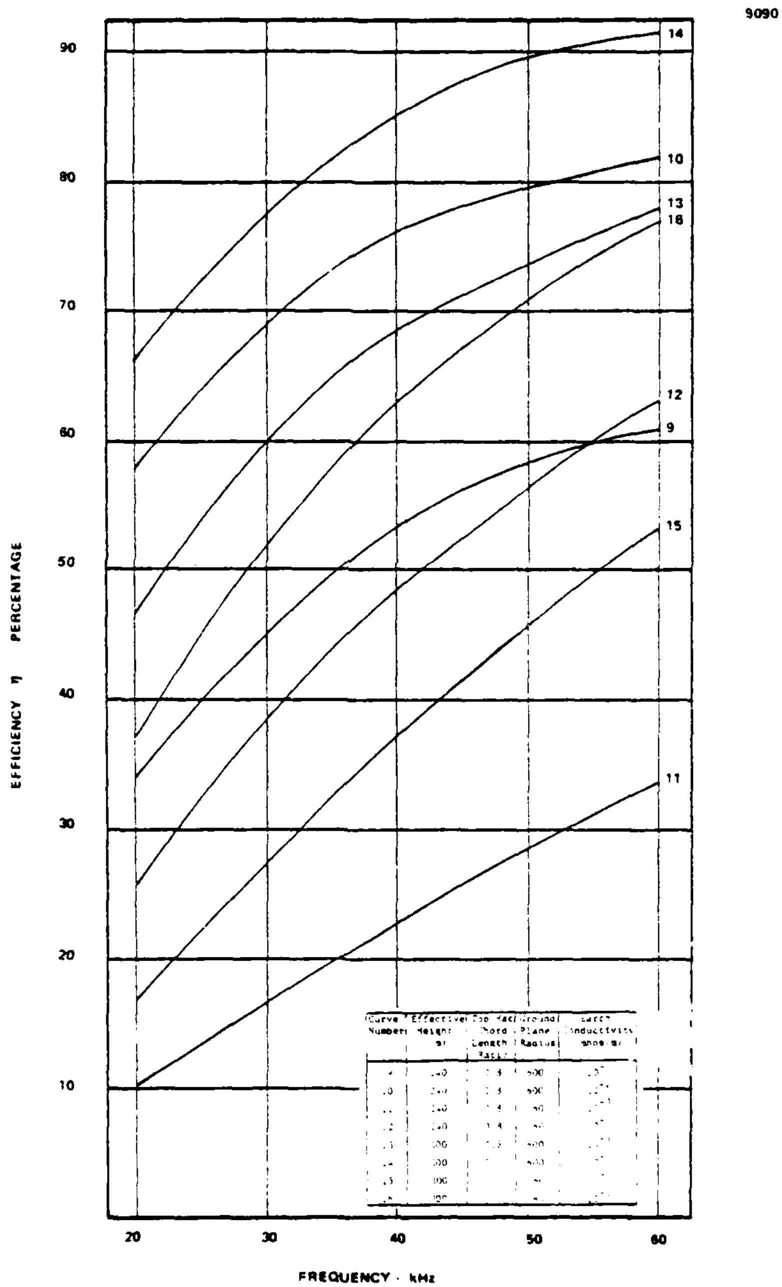
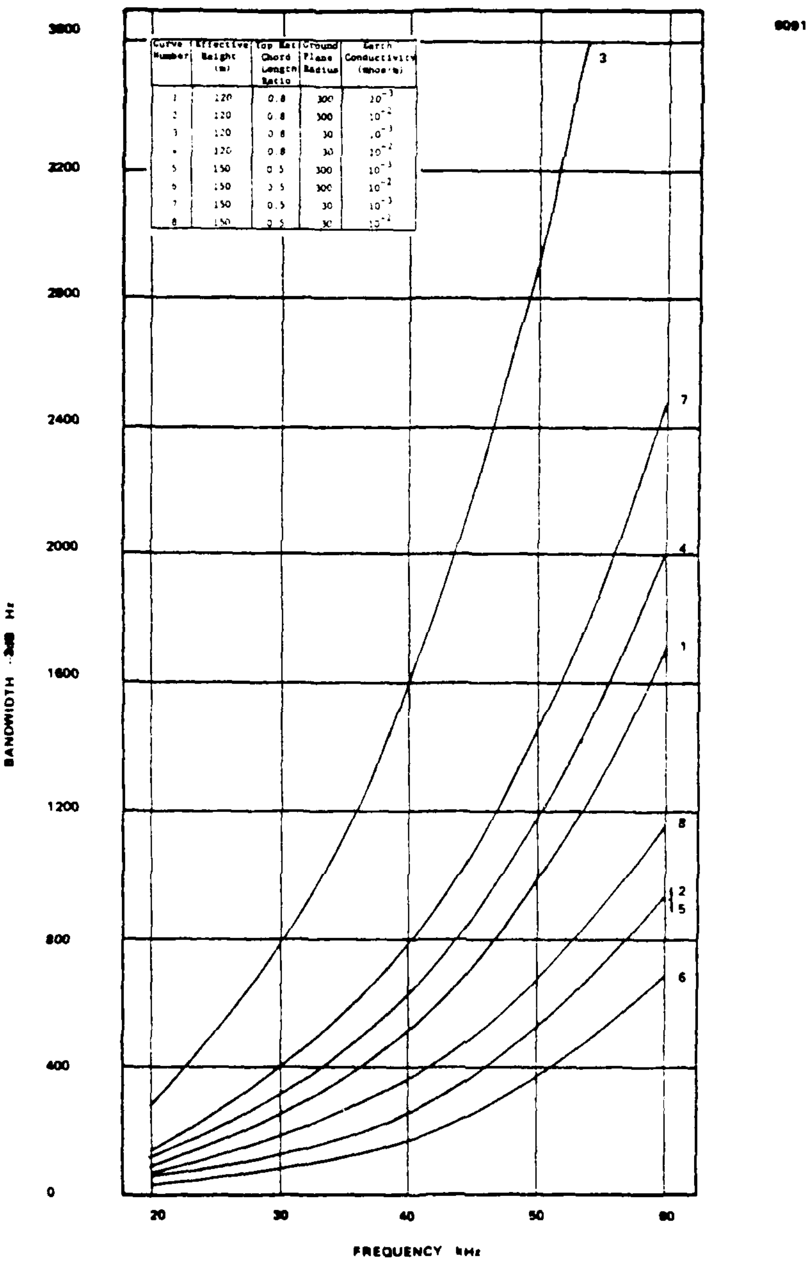


Figure 21. 600 m Tower Systems - Radiation Efficiency



Curve Number	Effective Height (m)	Top Hat Chord Length Ratio	Ground Plane Radius	Earth Conductivity (mhos/m)
1	120	0.8	300	10^{-3}
2	120	0.8	300	10^{-2}
3	120	0.8	30	10^{-3}
4	120	0.8	30	10^{-2}
5	150	0.5	300	10^{-3}
6	150	0.5	300	10^{-2}
7	150	0.5	30	10^{-3}
8	150	0.5	30	10^{-2}

Figure 22 300 m Tower Systems - 3dB Bandwidth

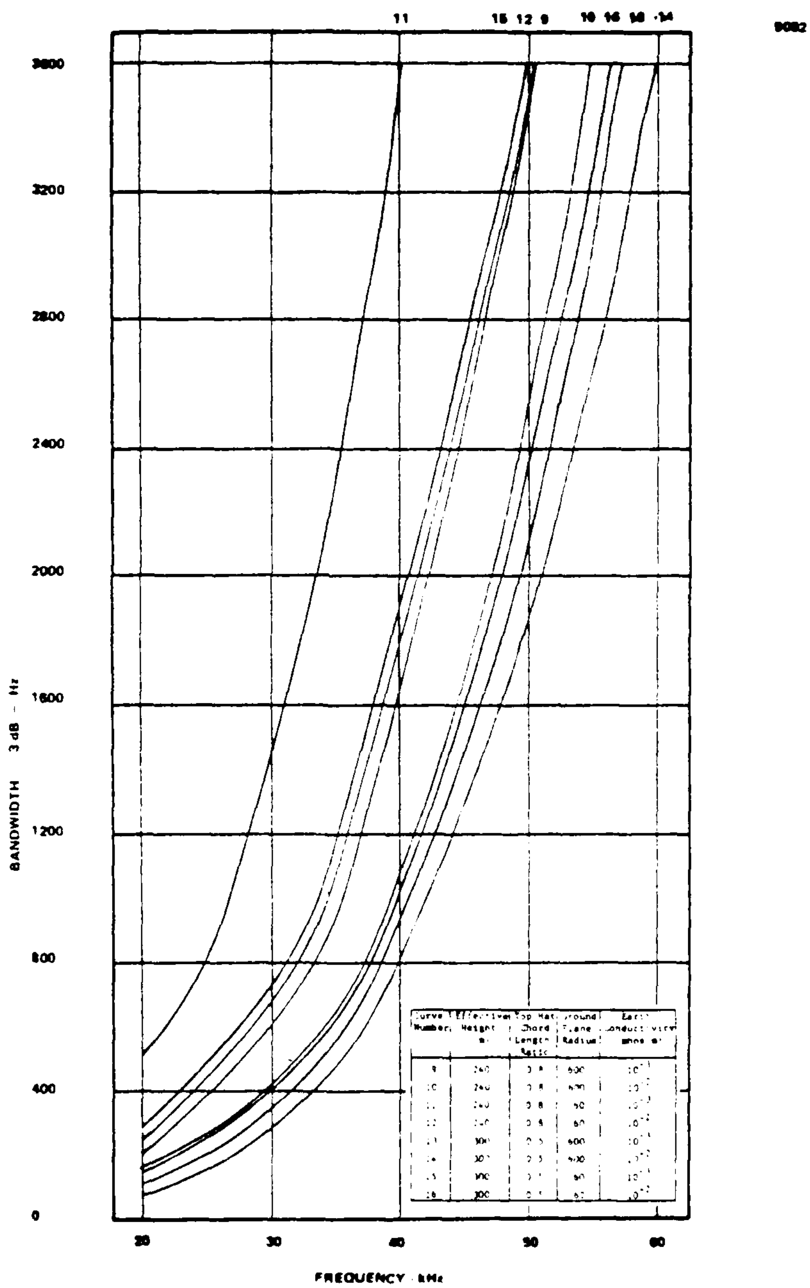


Figure 23 600 m Tower Systems - 3dB Bandwidth.

From these curves can be seen the effect of the individual parameters. For example, in all cases the radiation efficiency is higher when the earth's conductivity is higher. The radiation efficiency is also higher when the larger ground screen is used. In both cases, increased efficiency is obtained as a result of lower ground losses. It can also be seen that use of a shorter top hat chord length results in a greater effective height and this yields a higher radiation efficiency. This effect is caused by the negative current component in the active guy relative to the tower as explained in Section 2.

4-3.1.2 System Bandwidth. For each curve of radiation efficiency, there corresponds a unique curve of system bandwidth. The bandwidths plotted in Figures 22 and 23 are 3dB bandwidths that include the antenna tuning coil losses. In general, one always observes that the higher the radiation efficiency is, the lower is the system bandwidth. In all cases, it can be noted that the radiation efficiency-bandwidth product for the 600 m tower is greater than that of the 300 m tower.

In the case of the 300 m tower, some damping (loss resistance) is required to increase the system bandwidth in order to permit transmission of high data rate communications. For the 600 m tower the bandwidths are adequate and consequently no damping is required.

4-3.2 Mechanical Performance

In order to modify an existing tower system, consideration must be given to the load that the tower must support. In most cases, a safety factor of 2.5 has been considered in the existing system design to account for the affects of ice loading and high wind conditions. To maintain this same safety factor requires that replacement guys be the same in number, diameter and length as the original guys.

A top hat assembly, as described in paragraph 4-2.2 can easily exceed the structural capacity of the tower. The new top hat system must use guy material characterized by a high strength to weight ratio. The

traditional wire rope material is much too heavy to be used for the top hat design considered. Using wire rope would reduce the guy quantity to no greater than 3 or 4 and would limit the distance of guy anchors from the tower. A more suitable guy material is a product manufactured by Philadelphia Resins Corporation. This material uses a Kevlar inner core which exhibits the same strength as wire rope but weighs 80% less. A conductive surface can be applied to the Kevlar core.

Using the conductive Kevlar cable, at least 8 guys can be used in the top hat assembly without reducing the safety factor of the tower structural support.

4-4 DEPLOYMENT

4-4.1 Deployment Concept

The fixed location tower antennas do not have the mobility of the transportable tower antennas described in Section 3. Although the tower is fixed in location and, therefore, vulnerable to nuclear blast effects, a degree of survivability can be achieved by modifying a sufficiently large quantity of towers to increase the probability that some will survive. A mobilized operations crew and VLF/LF transmitter, as a unit, can be deployed to a surviving tower location, make the necessary electrical connections and begin operation. Relocation can be achieved by moving the unit to another surviving tower location.

Discussed within the following paragraphs are the modification requirements and approaches for converting an existing tower to a dual purpose antenna system

4-4.2 Site Requirements

The design and extent of modification to a tower is governed by the real estate surrounding the tower and owned by the station. Required is sufficient real estate to place new guy anchors and to install an

adequate ground plane. Towers located in rural areas are desirable, since few obstructions or restrictions may exist. Urban areas would restrict the distance from the tower for guy anchor placement and the length of ground plane radials. Easements may be required to locate the guy anchors and ground plane on real estate not owned by the radio or television station.

A survey of candidate tower locations should be accomplished to determine the suitability of the site and to establish the physical parameters for guy wire and ground plane design.

4-4.3 Installation and Set-up

Since the tower is a fixed location facility, the site modification is permanently installed. The new guy anchors would be poured concrete and the ground plane entrenched in the earth.

The ground plane radials and top hat guys can be transported to the site on reels. The top hat guys are raised by using a haul line running to the top of the tower. As each guy is raised, a rigger fastens the insulator to the tower eyebolt and the haul line is released to bring up another guy.

After each guy is up and fastened, the bottom end is fastened to the guy anchor eyelet and tautened. After all new guys have been installed, any unnecessary guys associated with the original tower configuration can be removed to minimize the overall weight which the tower must support. As a minimum, the top most level of original guys should be removed to minimize any mutual coupling with the electrical characteristics of the newly installed guy system.

The antenna coupler is also permanently installed by constructing an environmentally controlled shelter for the coupler. The base for the shelter is a concrete platform. A transmission line is installed between one of the top hat guy wires and the coupler output terminal.

4-4.4 Personnel Requirements

4-4.4.1 Ground Plane Installation. With trenching equipment a crew of three can install a 300 meter radius ground plane system in four days. A 600 meter radius system requires approximately seven days.

4-4.4.2 Guy Anchor Installation. Guy anchor installation involves backhoe excavation, concrete form construction, steel mesh reinforcement fabrication for the anchor eyelets and the pouring of concrete. One backhoe operator, four iron workers and two concrete workers should complete the installation of 16 anchors in four days.

4-4.4.3 Guy Wire Installation. The top hat guys will require two riggers (top of tower), four groundmen, one winch operator and one driver. Sixteen top hat guys will require three days.

4-4.4.4 Antenna Coupler Installation. The antenna coupler and shelter can be shipped to the site prefabricated, requiring only the installation of a concrete slab to which the coupler/shelter is attached. Slab construction requires earth excavation, concrete form construction, steel mesh reinforcement and concrete pouring. A crew of five should complete slab construction in one day. Another crew of five is required to assemble and attach the shelter/coupler and make the necessary electrical connections in one day after the concrete has cured.

4-4.5 Transportation Requirements

After the tower has been converted for VLF operation, no transportation requirements are foreseen. This does not consider any requirement to bring the transmitter to the site for periodic operation and maintenance.

4-5 COST ASSESSMENT

This section addresses the costs to modify an existing radio or television tower. The modification cost varies dependent upon parameters for the tower height, the guy wire system and the ground plane. The tower heights considered are 300 and 600 meters.

4-5.1 Assumptions/Methodology

It is assumed that a prime contractor is utilized to perform feasibility and design studies of designated towers and to specify design requirements for optimum configurations. The contractor is responsible for the design and fabrication of the modification components and is also responsible for modification installation, test and delivery of an operating antenna system.

Parametric cost estimates, varying by tower quantity, are presented for different physical parameters of the antenna system. Associated with each antenna of a production acquisition is an amount for RDT&E which is due to the need to tailor design each antenna installation. Total acquisiton costs, therefore, include RDT&E and production costs. The total acquisition costs are developed for a single antenna procurement and for incremental procurements of up to eighty (80) antennas of the same configuration. This can be extended further recognizing that unit costs decrease as production increases for the various transportable tower systems and are presented in Figure 24.

4-5.2 Acquisition

The acquisition cost and anticipated delivery schedule (months after contract award) for one antenna system as a function of system physical parameters are summarized in Table 3. These costs and multiple buy costs are presented in Figure 24.

Table 2. First System Acquisition

System Parameters		First System Acquisition Cost ($M)	First System Delivery (Months)
Tower Height (m)	Ground Plane Radius (m)		
600	600	3.3	24
600	60	2.7	24
300	300	2.5	24
300	30	2.2	24

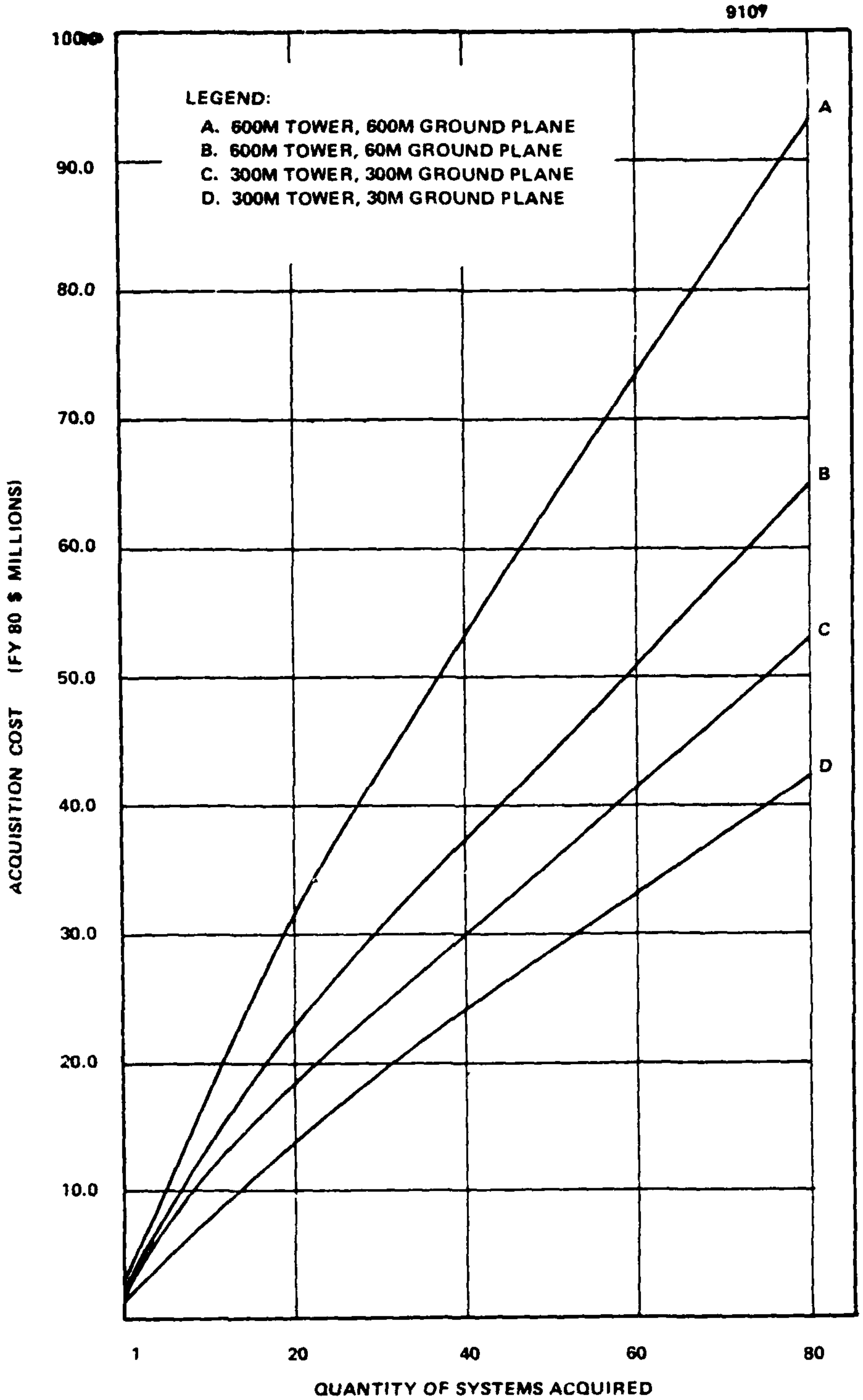


Figure 24. Total Acquisition Cost - Fixed Location Tower Modifications

SECTION 5

TETHERED BALLOON ANTENNAS

5-1 INTRODUCTION

Tethered balloons are recognized as a means for deploying a mobile or semi-permanent capability. A significant tethered balloon application is the SEEK SKYHOOK project which uses an aerostat to support a radar system 3.6 kilometers above the earth's surface. By applying the same engineering approaches, it is feasible to employ a tethered balloon to support a VLF/LF transmitting antenna.

Like the transportable tower antennas described in Section 3, a tethered balloon antenna may be stored until the post-attack period and then be deployed to a suitable site and launched. Such systems are mobile and can reach altitudes enabling the development of quarter wave length antennas at VLF/LF. This can be a significant advance in the state-of-the-art of ground-based VLF/LF antenna systems since radiation efficiency computed in this study are in excess of 70% at 30 kHz.

Performances achievable by tethered balloon systems, however, are traded for an increase of vulnerability to the environment. High wind conditions can prohibit balloon launch or even "blow-down" the launched system. Susceptibility to lightning is also a factor. A Faraday cage is used to protect the SEEK SKYHOOK aerostats.

Design attention must also be given to the tether material. The material must have a high strength-to-weight ratio in order to not exceed the payload that can be supported by a balloon at high altitudes. If the tether also serves as the antenna radiating element, it must have a conductive surface sufficiently thicker than VLF/LF skin depths. The diameter must also be large enough to provide sufficient system bandwidth characteristics for communication system operation.

Five balloon configurations are evaluated in this section. The first configuration utilizes a balloon to support a monopole tether. The antenna is 500 meters in length. Two ground concepts are considered for this configuration. One concept utilizes the conductivity of sea water as the ground. The second concept utilizes only the earth without man-made alterations. For this configuration, the radiation efficiency at 30 kHz is 65% for sea water and 8% for an earth-only ground. The second configuration utilizes a top hat tether arrangement. For this configuration, the performance is evaluated at an altitude of 500 meters and two ground variations which are: a) seawater, b) earth without a ground plane. At 30 kHz, the radiation efficiencies for the top hat tether configuration using sea water and earth with no ground plane are 73%, and 8% respectively. A third tethered balloon configuration, involves a conductive surface balloon to avoid the use of top hat tethers.

A fourth configuration, a variant of configuration 2, employs an umbrella top hat with a ground plane with a resulting radiation efficiency of 52% while for seawater the efficiency is 80%. This configuration is also evaluated using two ground variations (sea water, land). Radiation efficiencies of 76% and 13% at 30 kHz can be achieved with this configuration and the respective ground variations.

The fifth configuration examined is the quarter wavelength tether. This configuration employs a single tether supported by the balloon a quarter wavelength in altitude. This configuration can achieve 57% at 30 kHz over typical conus terrain and 72% over sea water. A summary of all of the above configurations is presented in Table 4 which will be referred to in the next portions of this section.

Although each configuration uses a tethered balloon to either support or enhance the antenna system, each configuration is limited by the payload which a balloon can lift. The state-of-the-art in balloon size and capability is considered in the evaluations conducted in this section. Different sized balloons and different tether materials can be

TABLE 3

SUMMARY OF TETHERED BALLOON CONFIGURATION

CONFIGURATION No.	SYSTEM CONFIGURATION	GROUND PLANE CONFIGURATION TYPE	QTY RADIALS	RADIAL LENGTH	MAXIMUM OPERATING ALTITUDE (METERS)
1a	Monopole	Conus	N/A	N/A	500
1a	Monopole	Sea Water	N/A	N/A	500
2a	Top Hat Tether	Conus	N/A	N/A	500
2a	Top Hat Tether	Sea Water	N/A	N/A	500
3a	Conductive Surface	Conus	N/A	N/A	500
3a	Conductive Surface	Sea Water	N/A	N/A	500
4a	Top Hat Tether	Conus	100	300	500
4a	Top Hat Tether	Sea Water	100	300	500
5a	Quarter Wavelength	Conus	N/A	N/A	3750
5a	Quarter Wavelength	Sea Water	N/A	N/A	3750

used with an attendant change in performance. A smaller system can be less difficult and time consuming to deploy and also less costly. The design, deployment and cost tradeoff issues are discussed further in the next sections.

5-2 ANTENNA DESCRIPTIONS

The physical and component characteristics of the four tethered balloon configurations are examined in the following paragraphs. These descriptions will provide the fundamental physical parameters for determination of the associated performance, deployment and cost parameters.

Each configuration uses an aerodynamically shaped balloon to reduce the vulnerability to blowdown from high winds. In most configurations examined, the balloon is used to support the radiating components of the antenna. Such balloons are available from several sources including ILC Corporation, Roven Industries and Sheldahl Company. Both ILC and Sheldahl concentrate on large special application balloon capabilities and have conducted special materials development programs to improve the strength of balloon fabrics as well as reduce their weights. The Raven Industries balloons are smaller than ILC and Scheldahl and are designed for general purpose applications.

For evaluation, only helium filled balloons have been considered. Other gases, such as hydrogen and methane, have explosive flammability characteristics and should be avoided. Hot air was not considered due to the requirement for a source of heat to maintain lift.

5-2.1 Monopole Tether Configuration

This configuration employs a single tether for the active element of the transmitting antenna and is the least complex of the tethered

balloon systems that are examined. No top-loading nor man-made ground plane is utilized in this configuration. Descriptions of the major components of this concept are provided below. The balloon is discussed in paragraph 5-3.2.

5-2.1.1 Radiating Element. The radiating element of this configuration is the vertical conductive tether supported by the balloon. For evaluation, this element is limited to a length of 500 meters. The quarter wave length tether system described in 5-2.4 examines similar systems at greater altitudes.

The monopole tether should be conductive and light weight. Such cables have been fabricated by Philadelphia Resins Corporation. These cables use an insulated inner core of kevlar to provide strength to the cable and to provide sufficient diameter for the braided wire conductive outer surface. To ensure that the antenna has adequate bandwidth at VLF/LF, a cable diameter of approximately 2 centimeters is required. Lower bandwidth results with smaller diameter radiating elements.

5-2.1.2 Ground Plane. A man-made ground plane is not included in this antenna configuration. For performance evaluation, conductivities of 5 and 10^{-3} mhos/meter are considered. The former would be representative of operation over salt water.

5-2.1.3 Antenna Coupler Van. The antenna coupler concept is similar to that of the transportable single tower described in 3-2.1.3. For the

monopole tether configuration, the tuning coil contains 130 turns of 3 cm copper tubing. It is 3 meters in diameter and 4 meters in height. The coupler is installed in a van trailer for mobility and environmental protection. An RF feed-through bushing exists at the top surface of the trailer for connection to the antenna terminal.

5-2.2 Top Hat Tether Configuration

This antenna configuration is similar to the classical top loaded vertical radiating antennas. Instead of a tower providing the structural support to the system, a balloon is used as illustrated in Figure 25.

5-2.2.1 Top Hat Tethers. Eight top hat tethers are used in this configuration. Each tether extends to a point 500 meters from the antenna coupler van and has an active total length ratio of 0.7. The diameter of the active tether is 4 mm.

5-2.2.2 Vertical Wire. The vertical wire of Figure 26 represents a monopole antenna 500 meters in height. The wire considered is 4 mm in diameter.

5-2.2.3 Antenna Coupler Van. The antenna coupler electrical characteristics can vary depending upon the ground plane utilized. For this antenna configuration, a tuning coil that contains 90 turns of 3 cm copper tubing should be sufficient to be compatible with any ground plane considered. Tap selection is used for the appropriate operating frequency and selected ground plane configuration. The tuning coil is 2 meters in diameter and 3 meters in height. It is contained within a van trailer for mobility and environmental protection.

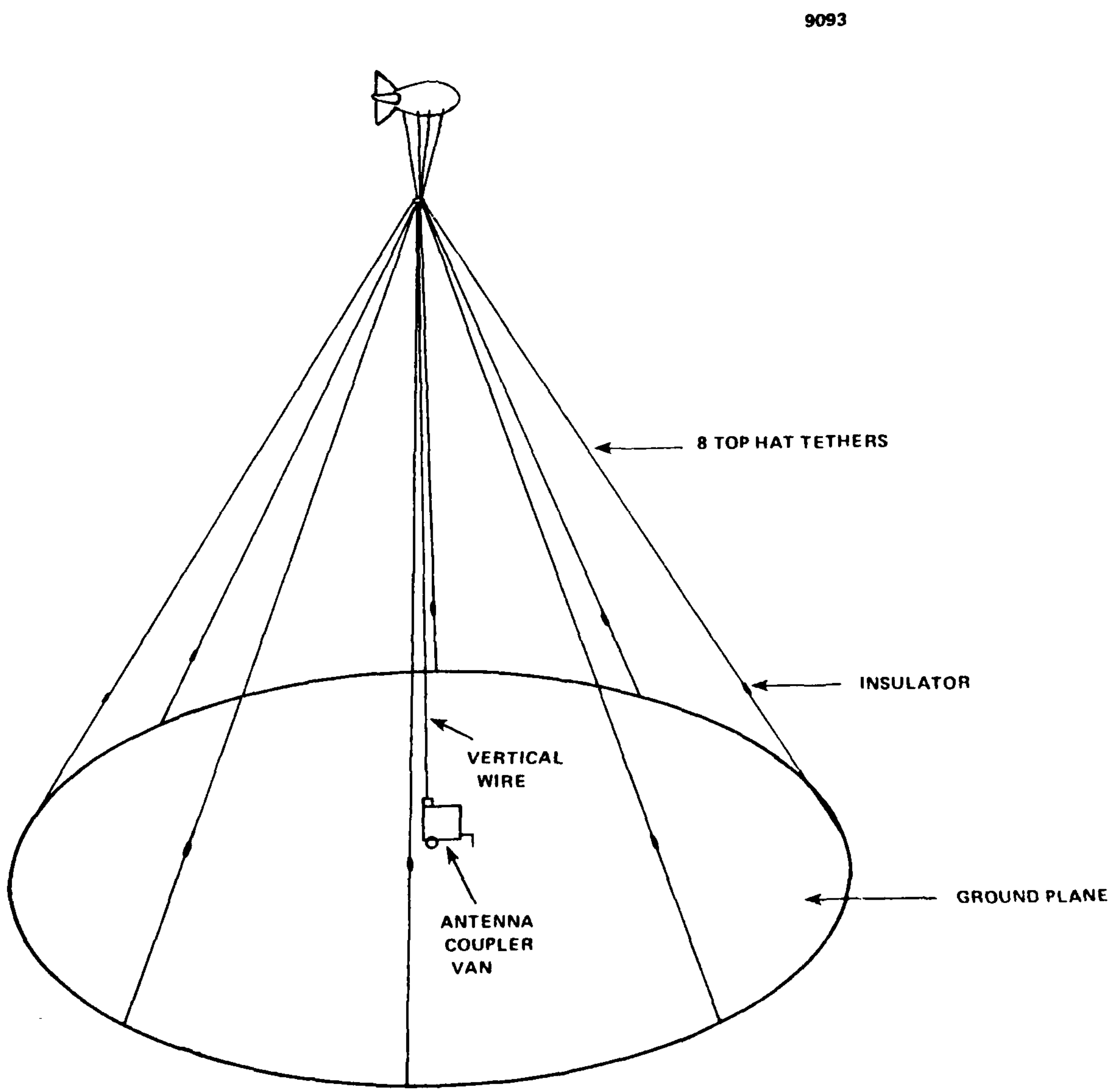


Figure 25. Top Hat Thether Balloon System Configuration.

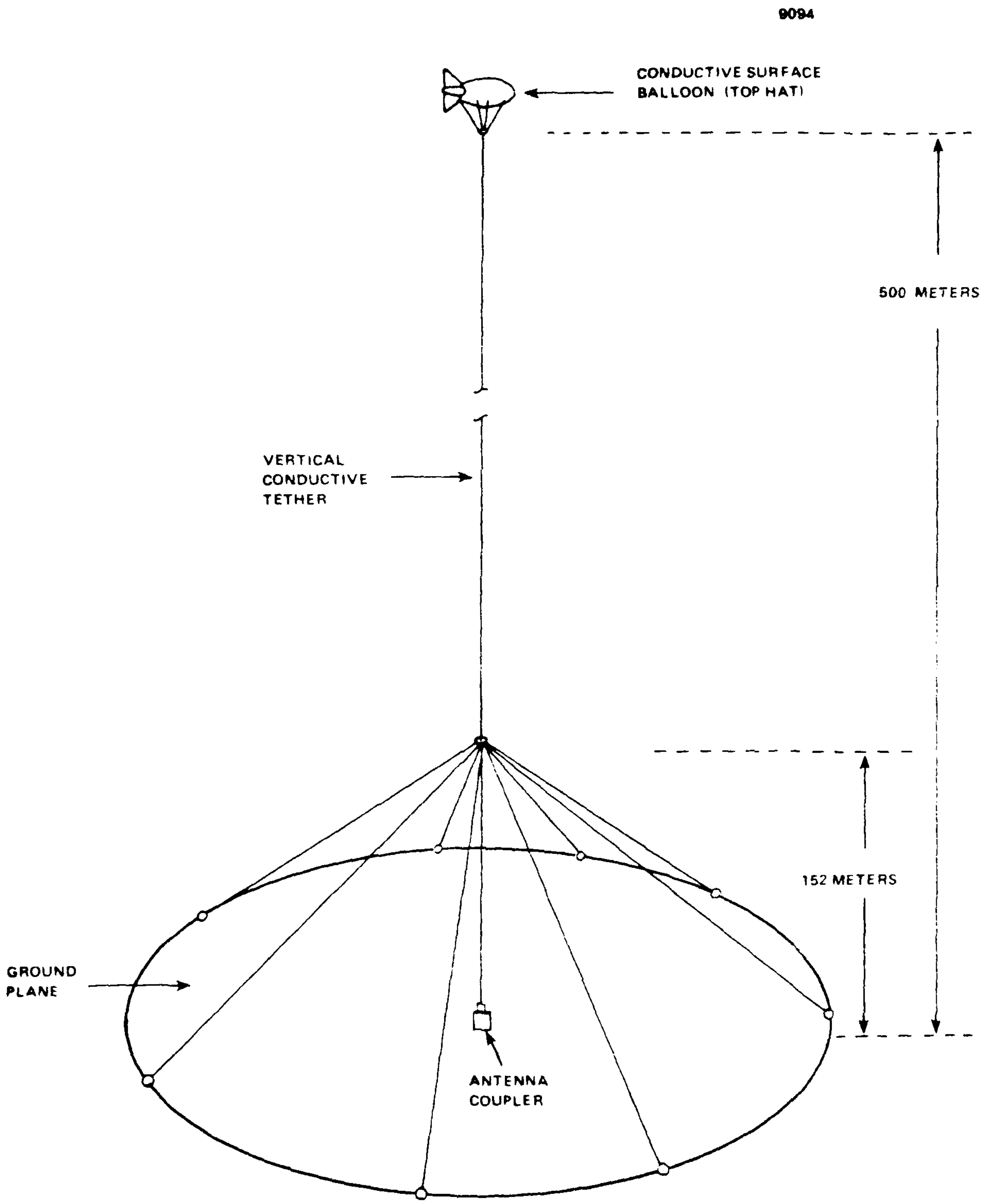


Figure 26. Conductive Surface Balloon System Configuration.

5-2.2.4 Ground Plane. For the top hat tether configuration, three different ground plane concepts are considered. These concepts are: 1) using sea water (σ = 5 mhos/m), 2) using low conductivity soil only ($\sigma = 10^{-3}$ mhos/m), and 3) using man-made alteration of low conductivity soil ($\sigma = 10^{-3}$ mhos/m). The man-made alteration involves 100 radials encircling the antenna coupler van. Each radial is 300 meters in length.

5-2.3 Conductive Surface Configuration

This configuration is evaluated as a possible alternative to a top hat tether system. A conductive surface is applied to the balloon. This surface is intended to sit as a top hat. Initial calculations indicate that a conductive surface with the thickness required for VLF/LF operation may result in a weight in excess of the bouyancy capability of the balloon. This is examined further in paragraph 5-3.2.

Figure 26 also illustrates the concept of the conductive surface configuration. Other factors that are considered in our evaluations are described in the following paragraphs.

5-2.3.1 Radiating Element. The radiating element in this configuration is the vertical wire shown in Figure 26. For evaluation this wire is 500 meters in length and 2 cm in diameter. Its construction is the same as that described in paragraph 5-2.1.1.

5-2.3.2 Insulated Tethers. Use of these tethers are optional since there is no effect upon the radiating characteristics. There is an effect upon the load which the balloon must lift.

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5-2.3.3 Antenna Coupler Van. For this antenna configuration, a tuning coil consisting of 126 turns of 3 cm copper tubing can satisfy the inductive requirements. The coil considered is 3 meters in diameter and 4 meters in height. The tuning coil is installed in a van trailer for mobility and environmental protection.

5-2.3.4 Ground Plane. Two ground plane concepts are considered for this configuration. The concepts are the same as described in 5-2.2.4.

5-2.4 Quarter Wavelength Configuration

Electrically short antenna systems are known to exhibit low radiation efficiencies. Ideally antennas should be of a length to enable resonance, however, the wavelengths at VLF/LF result in antennas that are nearly physically impractical. Based upon developments by the SEEK SKYHOOK program, the present balloon technology may enable the development of quarter wavelength VLF/LF transmitting antennas. Figure 27 illustrates the configuration of a quarter wavelength transmitting antenna.

5-2.4.1 Radiating Element. Quarter wavelength radiating elements at VLF/LF present two critical areas which must be considered in the design of the antenna. In comparision to system losses, such as ground loss, copper loss, etc., the radiation resistance can be greater by two or more orders of magnitude. As a result, the radiation efficiencies can be nearly 100%, except the system bandwidths are only several Hertz and unusable for communications system application.

It is necessary to ensure sufficient resistivity exists in the radiating element to offset the high radiation efficiency and provide the desired system bandwidth characteristics.

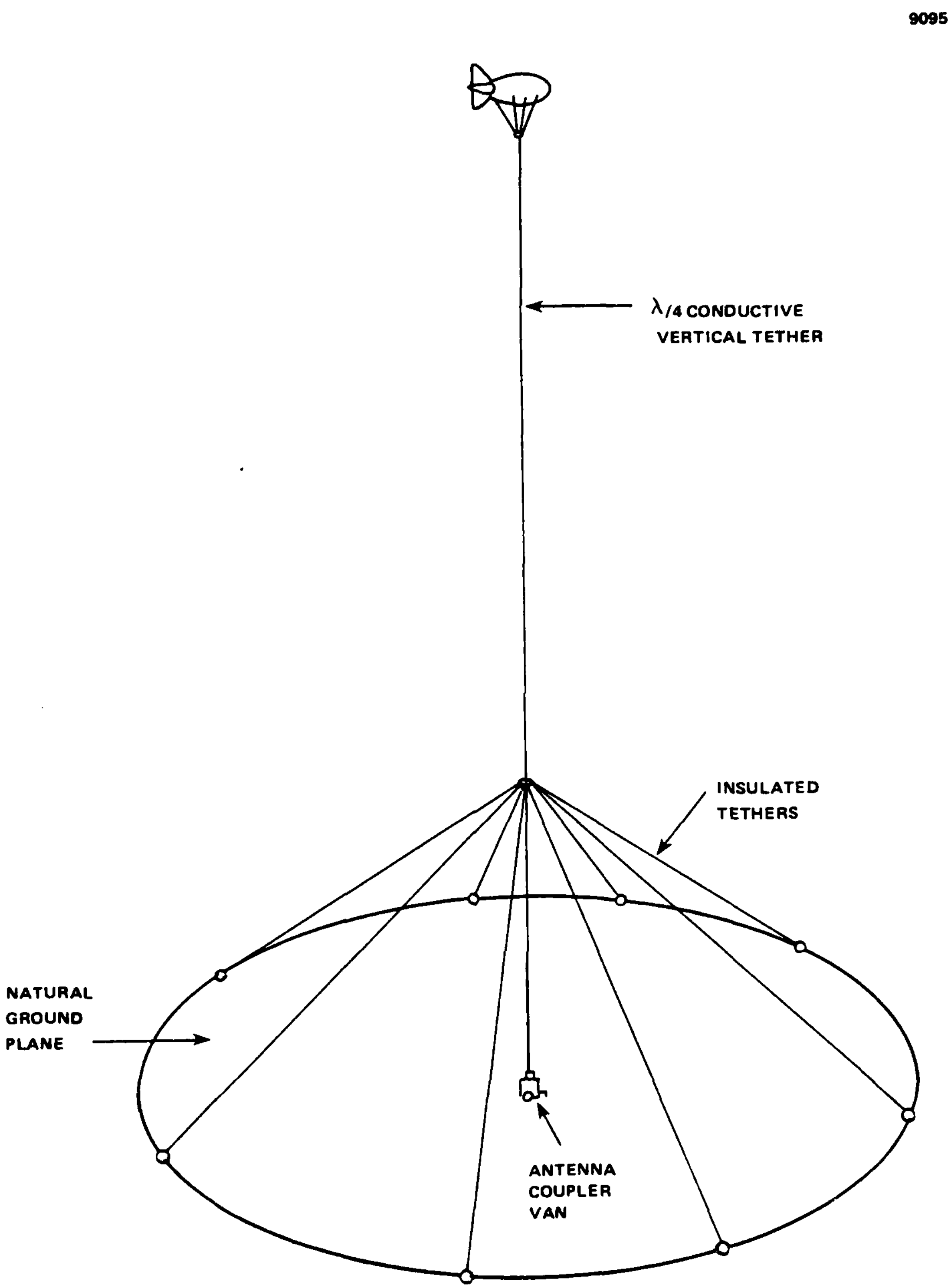

Figure 27. Quarter Wavelength Tether Balloon System Configuration.

Radiating elements of the lengths considered (up to 3750 meters at 20 kHz) must be sufficiently strong to support its weight yet be sufficiently high to be supportable by a balloon at altitude. The conductive surface/kevlar core cable described in 5-2.1.1 is a primary candidate for this application.

5-2.4.2 Insulated Tethers. The insulated tethers shown in Figure 28 are optional in the design of the antenna. They are included to minimize sway of the radiating element.

5-2.4.3 Ground Plane. A man-made ground plane is not included in this antenna configuration. For performance evaluation, conductivities of 5 and 10^{-3} mhos/meter are considered.

5-3 ANTENNA PERFORMANCE

Both electrical and mechanical performance characteristics of the tethered balloon configurations are derived using the methodology described in Section 2 and the configurations and physical parameters described in paragraph 5-2. Performance profiles are identified by configuration numbers and correlate with the configurations identified in Table 4.

5-3.1 Electrical Performance

Parametric profiles of radiation efficiency and system bandwidth for the tethered balloon antenna configuration are presented in Figures 29 and 30. The interrelationship of each configuration and its associated performance is discussed further in the following paragraphs.

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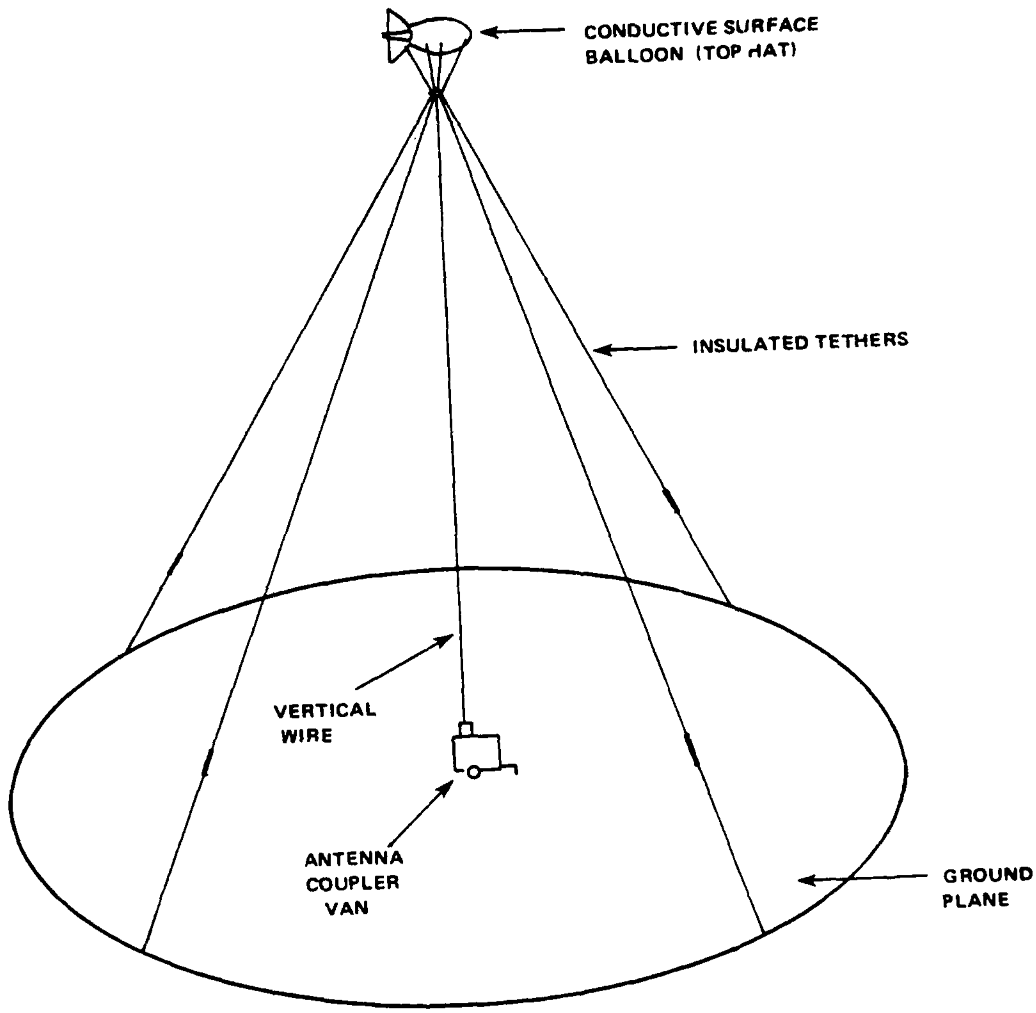
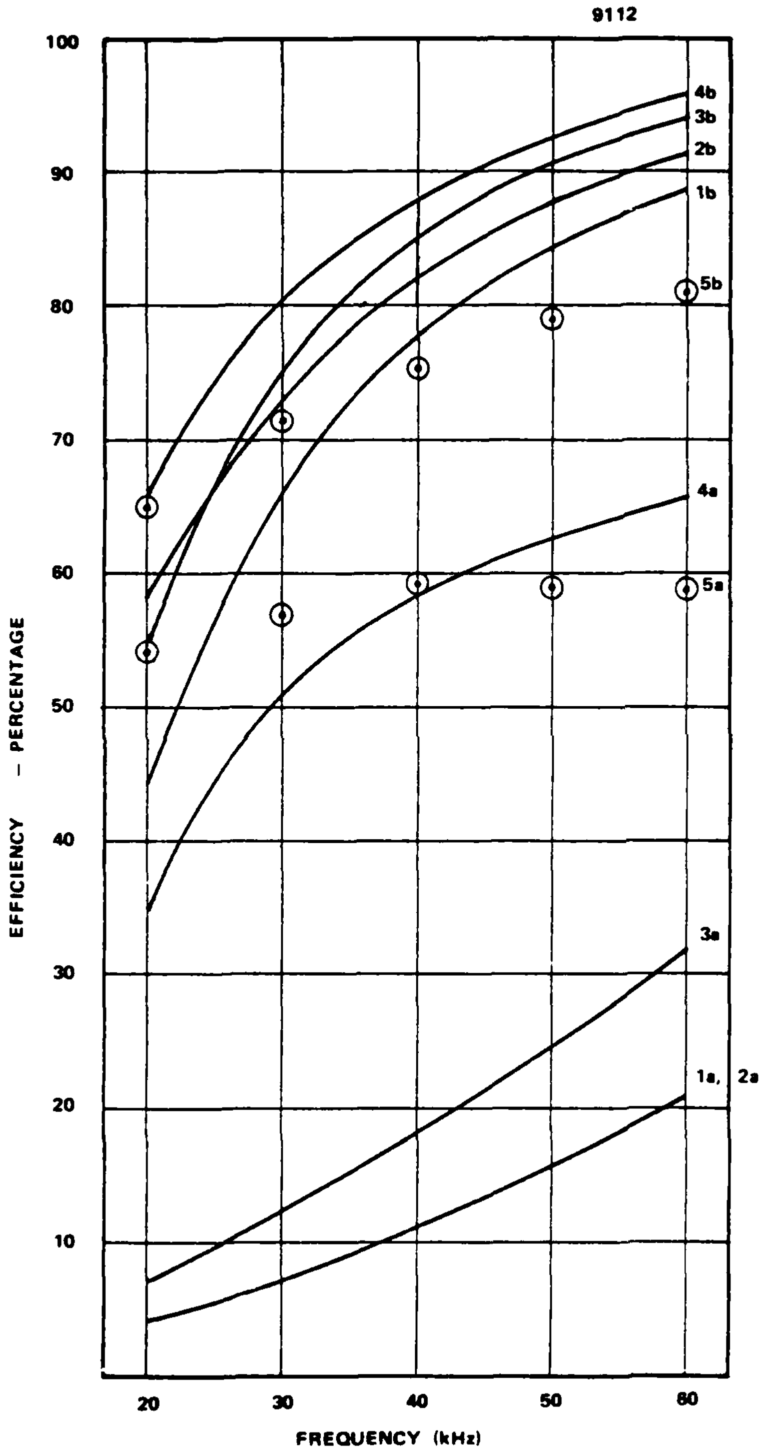


Figure 28. Insulated Tether Configuration.



1a) VR, w/o Top H., w/o GP, $\sigma = 10^{-3}$ mhos/m

1b) VR, w/o TH, w/o GP, $\sigma = 5$

2a) Vertical radiator, with top hat, w/o ground plane $\sigma = 10^{-3}$ mhos/m

2b) VR, with TH, w/o GP, $\sigma = 5$

3a) Vertical radiator, metallized balloon, w/o GP, $\sigma = 10^{-3}$ mhos/m

3b) VR, metallized, w/o GP, $\sigma = 5$

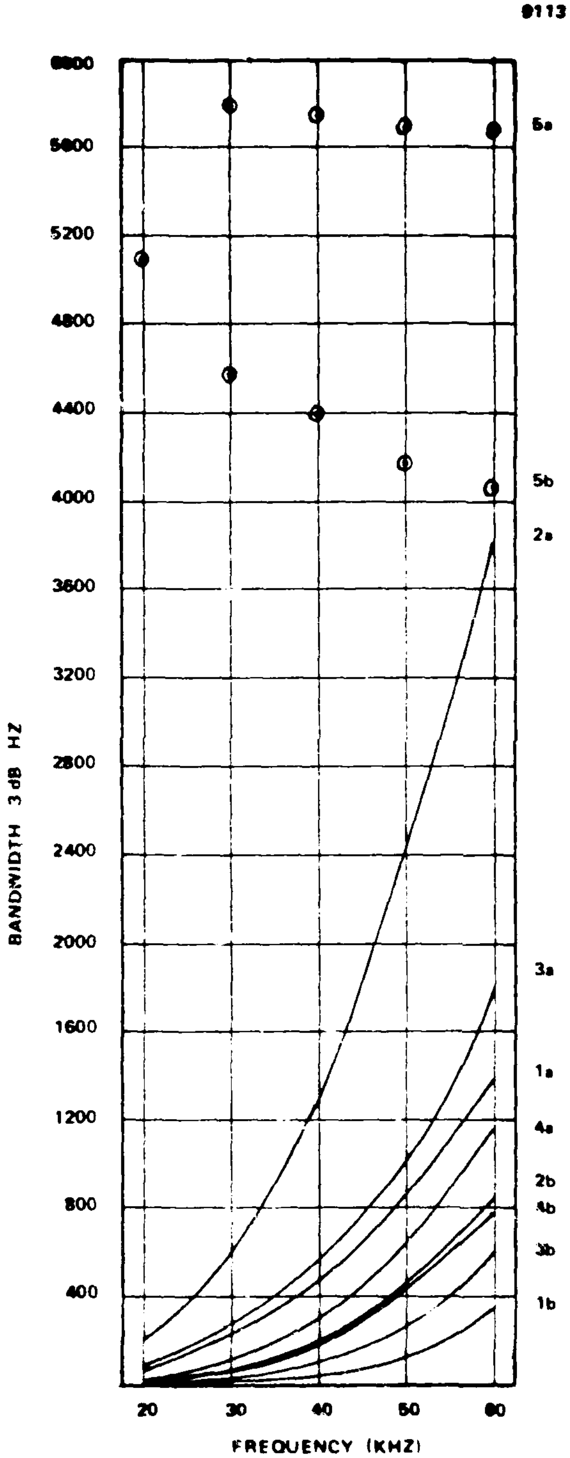
4a) VR, with Top H., w GP, $\sigma = 10^{-3}$ mhos/m

4b) VR, w TH, w GP, $\sigma = 5$

5a) $\lambda/4$ wavelength, CONVS

5b) $\lambda/4$ wavelength, seawater

Figure 29. Radiation Efficiency vs. Frequency



1a) VR, w/o Top H., w/o GP, $\sigma = 10^{-3}$ mhos/m

1b) VR, w/o TH, w/o GP, $\sigma = 5$

2a) Vertical radiator, with top hat, w/o ground plane $\sigma = 10^{-3}$ mhos/m

2b) VR, with TH, w/o GP, $\sigma = 5$

3a) Vertical radiator, metallized balloon, w/o GP, $\sigma = 10^{-3}$ mhos/m

3b) VR, metallized, w/o GP, $\sigma = 5$

4a) VR, with Top H., w GP, $\sigma = 10^{-3}$ mhos/m

4b) VR, w TH, w GP, $\sigma = 5$

5a) $\lambda/4$ wavelength, CONVS

5b) $\lambda/4$ wavelength, seawater

Figure 30. 3dB Bandwidth vs. Frequency.

5-3.1.1 Radiation Efficiency. The radiation efficiency of each balloon configuration studied is plotted in Figure 29. With the exception of the quarter wavelength monopole, the antenna wire diameter employed is 4 mm. In the case of the quarter wave radiator, curves 5a and 5b, seven strand, 40% conducting gauge 18 copperweld with an effective diameter of .3 cm is assumed.

Three significant features are manifest in the figure. First, there is a distinct advantage gained if any of the balloon configurations are deployed over sea water. Curves 1b through 4b, computed for a conductivity of 5 mhos/m, show a marked improvement in efficiency as compared to curves 1a through 3a, which are based on a conductivity typical of the Central Conus, i.e., 10^{-3} mhos/m. Second, the introduction of a ground plane greatly enhances radiation efficiency over poor conducting earth. This is evidenced by a comparison of curve 4a (ground plane) with curves 1a through 3a (no ground plane). Third, the efficiency of a quarter wavelength radiator is relatively high over both good and poorly conducting surfaces.

Consequently, in terms of enhanced efficiency, deployment over sea water is superior to land deployment. High efficiency over land demands the introduction of a ground plane. The quarter wavelength radiator exhibits high efficiency over sea water and land without the use of a ground plane.

5-3.1.2 System Bandwidth

For each curve of radiation efficiency depicted in Figure 29, a corresponding plot of system bandwidth as a function of frequency is illustrated in Figure 30. The bandwidths are 3dB bandwidths which include the antenna tuning coil losses.

The most pronounced effect exhibited in Figure 30 is the bandwidth possible with the quarter wavelength radiator. The bandwidth is in excess of 4 kHz at all frequencies over both good and poor conducting surfaces and is clearly superior to all of the remaining configurations. It should be recalled (Figure 29) that the radiation efficiency of the quarter wave radiator was at least 50%.

Figure 30 shows that in general the bandwidth is higher over poorly conducting surfaces. This is a consequence of the inverse relationship between efficiency and bandwidth; the higher the surface conductivity, the greater the efficiency. Hence, the bandwidth is smaller over a highly conducting surface such as sea water.

Bandwidth can be gained by increasing the antenna capacitance with the introduction of an umbrella top hat as shown in curve 2a. However, introducing a ground plane to improve efficiency reduces the bandwidth as shown by curve 4a.

The curves show a clear trade-off between bandwidth and efficiency. Based on this trade-off, the quarter wavelength radiator is the superior configuration, offering both efficiency (greater than 50%) and bandwidth (in excess of 4 kHz).

5-3.2 Balloon Performance

Based upon the theory developed in Section 2 one can calculate the useful payload as a function of altitude for a given aerostat volume and weight. Choosing for example an aerostat of 7080 cu meters volume and having a weight of 2722 Kgs. the variation of lift with height was calculated using equation 47. This function is plotted in Figure 31 and corresponds to the available lift at 30° latitude on a summer day. By the winter the air is slightly more dense, thus providing slightly greater lift. Although there is a latitudinal variation of air density it is not very significant.

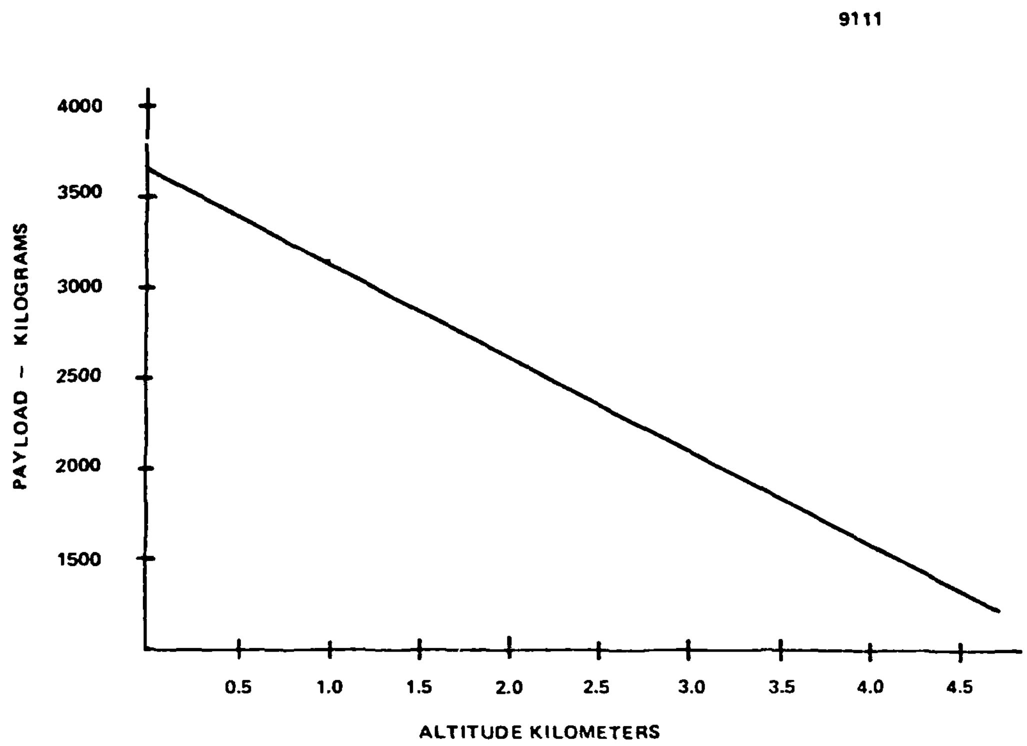


Figure 31. Altitude Versus Payload

Once the antenna weight and height (altitude) have been determined it is a straight forward matter to estimate the required aerostat volume. Conversely one might wish to effect a trade-off between aerostat size and hence cost versus antenna weight and hence performance.

5-4 DEPLOYMENT CONSIDERATIONS

5-4.1 Deployment Concept

The aerostat (balloon) is not intended as a permanent installation and at deployment will be taken from storage and trucked to the deployment site. The bag material will be folded in to a standard storage crate which has been nitrogen purged and sealed, and will be carried on a flat bed truck to the site. The bag material for a 7,080 cu. meter balloon weighs 2,270 kgms and can be unloaded at the site by means of a forklift or small crane.

In order to prevent tears in the fabric, a mat of non-static material must be laid on the ground under the collapsed balloon material. A cotton cloth can be used. The ground need not be flat but should not be rocky or have any sharp projections of a metallic or rock nature. The mat (for the above size balloon) will be approximately 30 x 30 meters.

A typical ground plane will be 600 meters in diameter with 100 radials. This area should be reasonably flat but the ground plane will not be buried and each radial will be 10 gauge copper and grounded at each end by means of ground rods. All ground rods at the center of the area will be bonded together. The radials will be spooled and transported by truck to the deployment site.

The tether cables will also be spooled and transported by truck to the site.

In addition, 64 bottles of helium, each carrying 138 pounds, will be required to inflate the balloon above the ballonet. This will require one additional truck with piping and valves for discharge and control of the helium flow.

5-4.2 Site Requirements

The deployment site has no special requirements other than it be reasonably flat and free of any sharp projections that could tear the balloon fabric. Desirable soil conditions would be 10^{-2} - 10^{-3} mhos to keep ground losses down and calm wind conditions will aid in getting the aerostat aloft.

5-4.3 Installation and Set-up

The tether truck with hoist equipment should be deployed adjacent to the central point of balloon ascent (see Figure 32). From the tether truck location the anchor eyes should be laid out at four points each 150 meters from the truck in a square formation. The tether ropes will then run through the anchor eyes and be returned to the hoist truck where the tether ring will be hooked to each tether. The radiator will then be passed through the tether ring. (Do not pull more than approximately 20 meters of radiator through the ring at this time - the rest of the radiator will be unwound as the balloon ascends).

Lay out the mat adjacent to the hoist truck and lay the balloon fabric over this with the helium valves on the opposite side from the hoist truck. Position the helium truck near the valves and commence inflating. When the bag tethers are exposed, hook them to the clamps on the radiator. Attach the radiator to the bottom balloon clamp, making sure all bag tethers are free of entanglement. Continue balloon inflation and start air into fins and ballonet. As balloon shape appears, check hoist tethers for freedom from entanglement and pay out individual hoists to maintain balloon shape and sufficient pressure to maintain at ground level (see Figure 33).

When helium load has been reached pay out tether hoists and allow balloon to rise to 2200 meter level (approximately $1/4\lambda$). At this

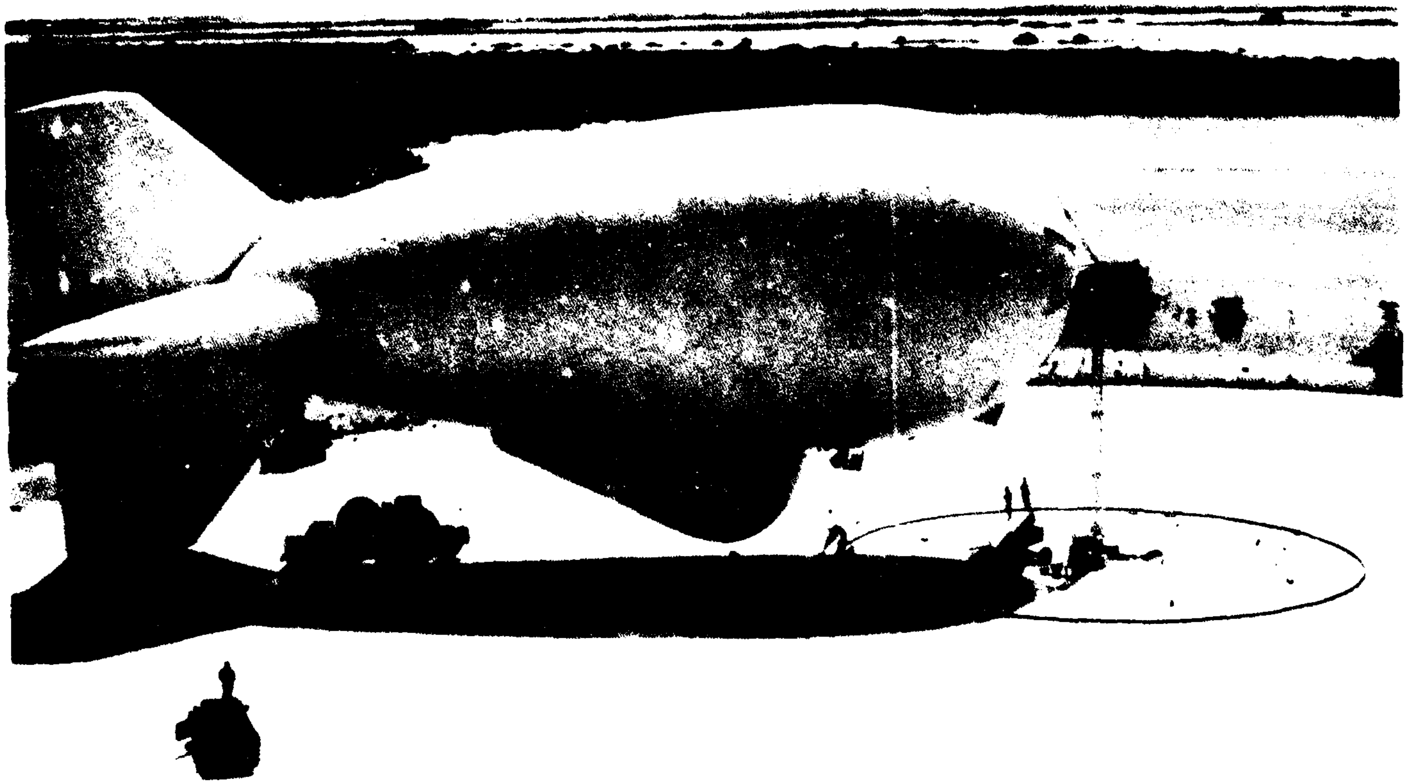


Figure [illegible]. Typical Tethered Balloon in Moored Position

Figure 33. Balloon Showing Tethers Attached to Aerostat

point radiator clamps should appear for clamping to tether ring. Finish clamping and allow all hoist tethers to rise so tether ring is at 150 meter altitude.

Unwind rest of radiator from spool and make connection to transmitter. If ground plane is to be used, lay out radials, drive ground stakes and ground all radials.

Site is now ready for R.F. transmission.

5-4.4 Personnel Requirements

Two hoist operators will be required to operate the tether hoist truck gear and radiator hoist gear. A ground crew of four additional men will be needed to handle tether cables, clamps and ground eyes. Balloon assembly and deployment will require another five men.

5-4.5 Transportation Requirements

Three flat beds of 8-10 metric tons each will be required for the balloon, ground plane and mat with the ground tethers on a special flat bed containing the tether hoist gear (see Figure 34). The radiator hoist truck with spooled radiator is shown in Figure 35. A special truck for the helium bottles and piping will also be required.

5-4.6 Summary of Deployment Parameters

The aerostat concept for support of a vertical radiator is highly mobile and intended to be deployed to any suitable land site and may even by deployed over sea water utilizing a small reasonably flat island or even a ship of any CV or LPH/LHA class.

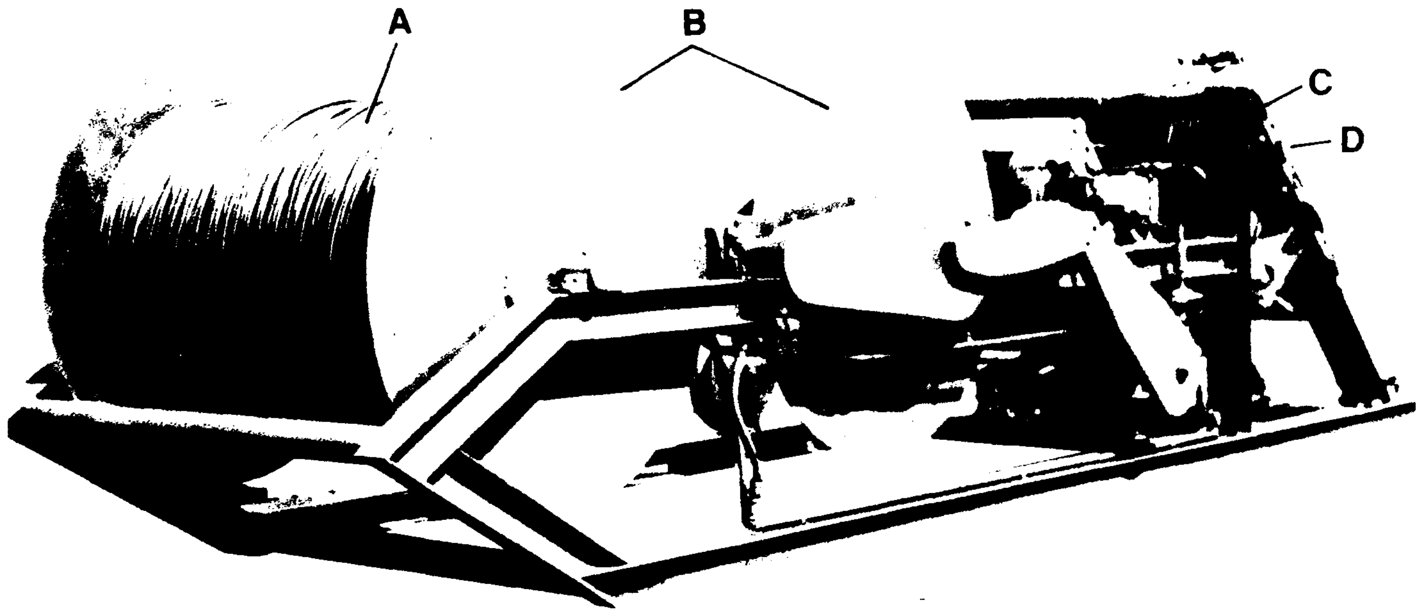


Figure 34. Tether Hoist Suitable for Flat Bed Truck.

Figure 35. Hydraulic Hoist Equipment for Very Large Aerostat Systems.

After equipment is deployed to the selected site, the radiator can be in use in a matter of a few hours or even less if the ground plane is not deployed.

The aerostat can quickly reach an altitude so that the radiator can be at 1/4 wavelength giving very high efficiency for R.F. radiation.

Less than a crew of twelve can completely deploy the radiator.

The aerostat will have sufficient bouyancy that minor punctures or tears will not prevent accomplishment of its intended mission.

5-5 COST ASSESSMENT

This section evaluates the cost for four tethered balloon antenna configurations. Each configuration includes an aerostat, one of which has a conductive surface. For evaluation the cost of an aerostat based system includes the basic equipment required to launch and keep the aerostat at altitude. There are many options that may be added to the basic system, e.g. sophisticated telemetry, lighting, etc., however such cost can add up to another $500K per tethered balloon antenna. The cost does not include a permanent mooring station which can add another $2,000K per system for the necessary site work, structured towers and support equipment.

The concept is for a transportable system. Dedicated vehicles are needed to store the aerostat and auxiliary equipment. The largest vehicle required is a winch assembly mounted on a reinforced flat bed trailer truck. Its function is to launch and retrieve the aerostat via a tether cable that is permanently mounted on the reel. A similar winch configuration is used by the SEEK SKY HOOK program. A current quotation was received for supplying a similar unit at $750K.

5-5.1 Methodology

It is assumed that a prime contractor is utilized to perform feasibility and design studies and to specify design requirements for the optimum configuration. The contractor is responsible for the design and fabrication of vertical wires and tethers; procurement of the aerostats and vehicles and; the test and delivery of an operational system.

Cost estimates are presented for different physical parameters of the antenna system. Associated with each antenna of a production acquisition is an amount for RDT&E which is due to the need to tailor design each antenna installation. Total acquisition costs, therefore, include RDT&E and production costs. The total acquisition costs are developed for a single antenna procurement and for incremental procurements of up to eighty (80) antennas of the same configuration. This can be extended further recognizing that unit costs decrease as production quantities increase. The total acquisition costs estimated for the various tethered balloon configurations are presented in Figure 5-12. The cost shown for each configuration, except the monopole tether, includes a supporting ground plane. This is estimated at $66K per system. A configuration without a ground plane would cost less.

5-5.2 Acquisition

The acqusition cost and anticipated delivery schedule (months after contract award) for one antenna system, as a function of system physical parameters, are summarized in Table 5. These costs, and multiple buy costs, are presented in Figure 36. To be noted in this figure is the significant cost difference between the monopole tether configuration and all of the others. This cost difference is due to the austerity of the configuration and tne use of an aerostat that is one-tenth the size of that used in the other configurations.

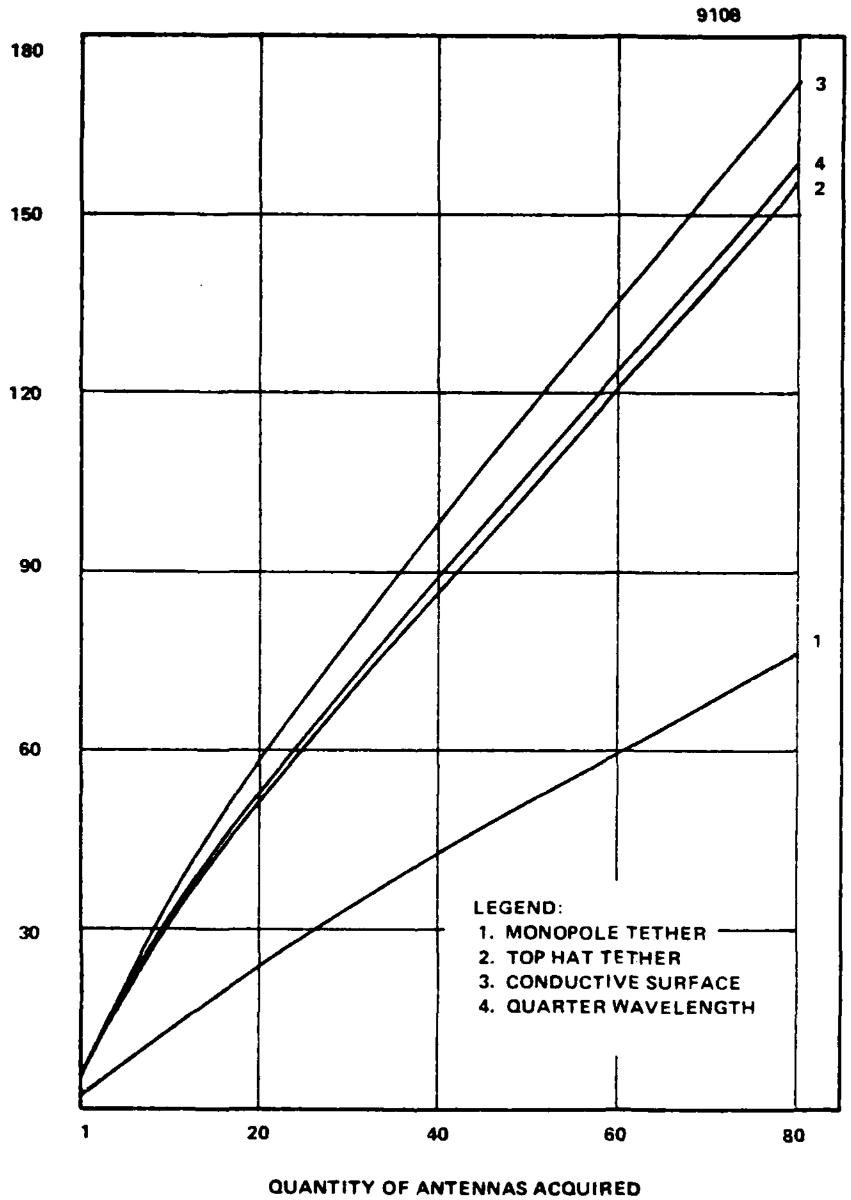


Figure 36. Total Acquisition Cost (RDT&E and Production - Tethered Balloon Antennas.

Table 4

FIRST SYSTEM ACQUISITION

Tethered Balloon Configuration	First System Acquisition Cost ($M)	First System Delivery (Months)
Monopole	2.2	18
Top Hat Tether	4.3	24
Quarter Wavelength Tether	4.4	24
Conductive Surface	4.7	24

5-5.3 Helium Costs

A significant portion of the cost for any of the tethered balloon configurations is the cost of helium. Assuming four launches per year for training purposes, the annual helium cost for a 7,000 cubic meter aerostat is approximately $72K.

APPENDIX

LIST OF SYMBOLS

A	=	area
a	=	equivalent length of top hat
B	=	radial distance from tower to guy anchor
B_o	=	bouyancy of helium in air
BW	=	3 dB bandwidth
b	=	length of radial ground wire
C	=	capacitance
C_D	=	wire drag coefficient
c	=	normalized wire radius
C_p	=	catenary parameter
D	=	tuning coil diameter
e	=	wire elongation
E	=	Modulus of elasticity
d	=	wire diameter
F	=	solenoid inductance factor
FL	=	freelift
f	=	frequency
g	=	acceleration of gravity
h	=	actual antenna height
h'	=	chord length of active guy
h"	=	height above ground of the end of active guy wire
I	=	antenna current
K	=	correction factor for proximity effects on inductor
k	=	correction factor for wire capacitance
L_b	=	balloon lift or payload
L	=	inductance
ω	=	length
MW	=	molecular weight
N	=	number of ground radials
n	=	number of turns of wire in solenoid
P_{rad}	=	radiated power
R_c	=	tuning coil resistance

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R_g	= ground loss resistance
R_{rad}	= radiation resistance
s	= sag of wire
S	= active guy length
SG	= wire specific gravity
T_{max}	= maximum wire tension
V_{max}	= maximum antenna voltage
Vol	= volume
$V\infty$	= wind speed
W	= total weight of wire
W_{bag}	= weight of balloon bag
W_{ice}	= weight of ice per unit length of cable
WF/ρ	= wind force per unit length
W_w	= wire weight per unit length
X_c	= capacitance reactance
X_l	= inductive reactance
α	= capacitive top loading factor
β	= wave number
ΔP	= differential density
ΔR	= incremental ground loss relative to perfect conductor
δ	= wave tilt
ε_o	= permittivity of free space
ε	= relative dielectric constant
λ	= wavelength
η	= efficiency
θ	= angle between wire and horizontal at support
σ	= conductivity
ρ	= density
μ_o	= permeability of free space
μ	= magnetic permeability
ν	= wire tensile strength
ψ	= loss tangent angle
ω	= angular frequency

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